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PRINCIPLES OF ENVIRONMENTAL STRESS ON SOLDIERS

ENVIRONMENTAL PROTECTION SECTION

Research and Development Branch

Military Planning Division

Office of the Quartermaster General

25 August 1944

Reissued February 1947

U.S. Quartermaster Corps. Military Planning Division.
Climatology and Environmental Protection Section

CONFERENCE ON THE

PRINCIPLES OF ENVIRONMENTAL STRESS ON SOLDIERS

For the Purpose of

Developing a Climatic Index Suitable for Mapping Purposes
for the Protection of Troops Operating in All Climates

Climatology & Environmental Protection
Research and Development Branch
Military Planning Division
Office of The Quartermaster General

25 August 1944

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*These charts are included by the courtesy of the Bureau of Standard's Textile Foundation.

PREFACE

These are not strictly the minutes of a meeting - if by the term "minutes" is meant a brief and formal summary of a conference in curt and outlined form. Such a summary would seem useless with such a preponderance of material on a subject so vast. Instead this is an attempt to reconstruct the papers as they were presented together with a small amount of the welcomed comments and criticisms which were offered by our guests. We deeply regret that we were unable to include all the discussion. The omission arises not from any editing of the dialogue; but simply because the remarks were not recorded at the time, and we feared lest we might do an injustice to our kind critics, if we put inadequately remembered sentences into their mouths. We hope that this summary will bring more comments from them.

In addition to what was actually said at the meeting, an appendix has been added with such information as may be necessary to put the index in usable form. The index as it now stands does not represent a final piece of work. Instead it is a first and tentative approximation. It is hoped that everyone will use it as he sees fit, and report either correlations or discrepancies to us, so that it may be improved.

The Climatology & Environmental Protection Section
1 December 1944

LIST OF ATTENDANCE

1. Visitors:-

Capt. L. L. Adamkiewitz, Naval Medical Research Institute
Lt. Col. T. F. Hatch, Armored Medical Research Laboratory
Commander F. C. Houghton, Medical Department, U. S. Navy
Surgeon H. F. Fraser, Industrial Hygiene Research Laboratory
Lt. C. R. Spealman, Naval Medical Research Institute
Lt. C. Taylor, Wright Field
Dr. H. S. Belding, Harvard Fatigue Laboratory
Dr. H. F. Blum, Naval Medical Research Institute
Mr. Gerald C. Bristow, U. S. Weather Bureau
Dr. C. F. Brooks, Blue Hill Meteorological Observatory
Dr. A. C. Burton, National Research Council of Canada
Dr. Dana Coman, John Hopkins University
Dr. Richard Day, Climatic Research Laboratory
Dr. Lyman Fourt, Textile Foundation, Bureau of Standards
Dr. Goldthwaite, Personal Equipment Laboratory, Wright Field
Dr. Milton Harris, Textile Foundation, Bureau of Standards
Dr. Ellsworth Huntington, Yale University
Dr. Robert G. Stone, Army Air Forces
Mr. Herbert C. S. Thom, U. S. Weather Bureau
Dr. C. W. Thornthwaite, U. S. Agriculture Department
Mr. Marvin VanDilla, Climatic Research Laboratory
Dr. Samuel VanValkenburg, Clark University
Commander A. R. Behnke, Naval Medical Research Institute

2. OQMG Representatives:-

Colonel Georges F. Doriot, Director Military Planning Division
Lt. Col. D. B. Dill, Assistant for Product Analysis
Major R. M. Ferry, Test Section
Dr. F. R. Wulsin, Test Section
Dr. L. T. Williams, Textile Section
Major Paul A. Siple, Climatology & Environmental Protection Sec.
Major Weldon F. Heald, " " " "
Dr. Jesse H. Plummer, " " " "
Mrs. Margaret I. Cochran " " " "
Mrs. Elizabeth Schickele " " " "
Mr. Malcolm Murray " " " "
Mr. David H. Miller " " " "
Miss Rose Sachs, " " " "
Mrs. Jane Westbrook " " " "
Mr. John P. Bader " " " "

CLIMATIC INDEX

Minutes of Meeting, 25 August 1944

The meeting was called to order at 1015 by Major Paul A. Siple, who introduced Colonel Georges F. Doriot.

COLONEL DORIOT:- We are very happy to have you. We are also very proud. A group such as this is distinguished by its intelligence, and the war has called upon you to use that intelligence in helping us provide adequate clothing and equipment for at least seven million seven hundred thousand men. Other sources furnish their products to a limited number only. Only a limited number, for example, use 150 millimeter guns which ordnance furnishes; the same is true of the other Corps, but every person in the Army will benefit or suffer according to how quickly the Quartermaster does its work. There has been, in the past, no systemized body of knowledge which concerned the food, clothing and shelter for the human being. I must look to you to see that the small knowledge which already exists is increased and developed so that the Military Planning Division will be able to furnish far better items than have heretofore been available. I understand that you cannot chart the course very accurately, but the wavy line of the progress must be determinable within certain boundaries. In clothing for cold weather, we have made progress. Our knowledge of hot weather clothing is, however, still very limited; and I feel quite distinctly that we have little or no knowledge on the subject of wet cold. We have a man in the nude. We have to dress

him, and we can do anything we want. We are now beginning to realize that something can be done to keep his body healthy and efficient. Industry will follow the direction of our knowledge. There is much still to be accomplished. This is no time to shorten the research program. The war in Europe may be progressing beyond our hopes, but the scientific research of the Quartermaster must progress with unslackened speed regardless of when the war may end.

Major Siple then thanked Colonel Doriot and introduced Lt. Col. D. B. Dill.

COLONEL DILL:- In view of the introduction by Colonel Doriot, there is little left for me to say except to reinforce what he has said and to emphasize particularly one statement he made. This is certainly a time to continue research rather than to consider plans for curtailment. Do you know that the Navy considers every battleship and every aircraft carrier to be essentially a research project? I have not heard of any immediate trend to discontinue the construction of those craft.

Another argument which was implied in what Colonel Doriot said is that no project ever reaches a state of perfection. It is also a fact that a longer time may be required to progress from 80% perfection to 90% perfection, than was required to gain the original 80% in the first place. The difference between 80 and 90% may mean the difference between success and failure in a military operation. There are then two fields in which we must work, first, to spread new ideas, and secondly,

to further perfect items in which the Quartermaster is interested.

Our Canadian friends have recently initiated a system at these meetings which we would do well to follow. (1) No meeting of this sort should be adjourned without a definition of a further course of work; (2) no meeting should be adjourned without definite assignment of future work, nor without a date when at least a portion of the work is to be completed.

MAJOR SIPLE:- The specific problem confronting us is the development of an index which will tie laboratory tests together with the experiences in the field. We are searching for a quantative means of determining adequate quantities of clothing, beds and shelter and for a way in which these can be plotted on maps. The laboratories have given us certain factors. They have worked out those factors with care and in great detail. The Quartermaster is confronted with the groups of men in the field whose comments are apparently at varience with the laboratory ideas. This difference is probably due to a group of variables which cannot be ideally measured in a laboratory where sunlight, high wind velocity and many other factors are by necessity absent; therefore, there should be some reliable means of extrapolating from the laboratory tests to the knowledge which has been accumulated in the field throughout the years. There is not enough time during war and there is too much danger in waiting until after supplies have reached a region to determine whether or not supplies are adequate for the time and place. We must be able to predict that the clothing and equipment will

be completely adequate under normal conditions so that under subnormal conditions little or no danger is encountered.

For this reason, we have asked together today an extensive group of physiologists, physists and climatologist so that three portions of this study may be brought together; the climatic conditions as they are known by the climatologists; the reaction of man's body as it is known by the physiologists; and between them the physical laws of heat transfer through clothing. We have chosen as the temporary chairman of our meeting today, Dr. Jesse H. Plummer, who is a physicist from the glass industry. He has studied this problem deeply so as to find laws through the medium of Physics for integration between laboratory and field.

In this endeavor, we have several objectives:

(1) The construction of a comparative index with which to compare different climatic strains in all parts of the world. With such an index, we could map the world for the effect of climate on human beings. These maps would not only show the type of clothing needed, but would predict where trouble might be encountered. We know, roughly, where we have jungle and desert, but the intensity of the strain under which man's life may be endangered is still generally unknown.

One way of measuring the climatic strain can be obtained from a thermal analysis. We know that the body produces heat and that for life to be sustained this heat must be lost at an average rate equal to the rate of production, otherwise the

body temperature will steadily rise or fall until death occurs. The heat produced by the metabolism must then be equal to the sum of the heat lost by conduction through the clothing, convection from unclothed areas, radiation from the clothing and skin, and evaporation from the body surface or wet portions of the clothing.

Not all of these factors are always losses. Under conditions of high temperature and in the sunshine, it is quite possible for the body to gain heat through convection, conduction and radiation. The essential feature, however, is that in order to maintain a constant body temperature all of the heat which is produced or carried into the body by exterior conditions must be lost.

This provides us with a means of calculating an index of climatic strain, as we can measure quite accurately the quantities of heat transferred through the various channels. For instance, if the climatic conditions and the clothing have been defined, we may calculate the heat production that is required in order to maintain a balance. On the other hand, if the heat production and the climatic conditions are defined we may calculate the amount of clothing that is required to keep a man in equilibrium.

As the critical danger always lies in extreme conditions, we suggest the use of two indices. The hot weather index may be defined as the limits of work which men may safely accomplish without raising their temperature. For cold conditions, the

index may be defined as the amount of clothing necessary to maintain equilibrium in standing men. Another way of defining a cold weather index would be the amount of insulation required to provide eight hours of comfortable sleep.

In this way, we could map the entire world and these maps would show the danger zones where severe heat strain may occur, as well as damp cold areas where trench foot would be prevalent.

These maps would not be expected to evaluate precisely the strain on any given individual but we do expect them to mark the areas of the world where the maximum protection must be provided for everyone. In addition, they will furnish a quantative estimate of the strain involved. Any individual, however, may feel more or less strain or require more or less protection than that estimated.

In this way, we can map the entire world, and these maps will show the danger areas where severe heat strain might occur as well as the damp cold areas where trench foot would be prevalent.

(2) The construction of clothing designed to make the most efficient use of the various avenues of heat loss under natural conditions. The indices provides a means of weighing these different avenues, and these in turn will provide accurate information as to how the clothing should be constructed. In the past we have designed clothing as if it were to solve a single problem; but if we are aware that, in one section of the world, the problem of human heat tolerance is 90% radiation and only 10% wind, then clothes can be so designed as to take the

greatest possible advantage of these two factors.

(3) From a human standpoint, we are also interested in the single effect of different types of heat loss registered by a single sensation in the human body. The psychological sensations of disagreeable cold, pleasant comfort and oppressive heat are important to the efficiency of the man even though the danger point may not be reached.

Our goal today is to establish an index which is satisfactory to the physiologist, which follows physical laws, and which can be used by the geographers and climatologists.

If there is time later in the afternoon, it may be possible to discuss the formation of a meteorological instrument which would register the same kind of heat stress which is felt by man. The Weather Bureau cannot establish a human testing laboratory at all of its locations, but it could give us some measure in a heat flow term which would represent the combined stress.

Since we cannot weight the single sensation on the human body until we have analyzed its four causes, we have divided the agenda into four parts: convection, conduction, radiation and evaporation. Following the review of each, we have asked for particular discussion of the problems by various members present -- but we are hoping that everyone will be free to comment, criticize and suggest.

At this point, I should like to turn the meeting over to Dr. Plummer.

SECTION I - CONVECTIVE HEAT TRANSFER:

DR. PLUMMER:- The first topic on the program is the discussion of the influence of convection upon the heat losses from the human body. Winslow, Herrington, and Gagge* have studied the effect of wind velocity upon convection and found that the convective heat transfer was proportional either to the wind velocity or to the square root of the velocity. Unfortunately, the experiments were based upon a relatively small range of air movement, and at high wind velocities there is a considerable difference in the values obtained from the two formula.

To generalize Winslow, Herrington, and Gagge's results so that they may be applied with confidence to high wind velocities, it is necessary to assume that the convective losses from the body are the same as those from a cylinder whose diameter may be found by comparison with physiological data.

Upon examining the literature within the last ten years, it is evident that there is a considerable amount of confusion existing in the relationship between convection and wind velocity. Some investigations show the square root law to be valid, others require different powers of wind velocity such as the 0.55 power, 0.6 power, 0.66 power, or even higher powers.

Within the last five years, much of this confusion has been eliminated through the application of dimensional analysis to the sur-

Gagge, Herrington and Winslow, The American Journal of Physiology, 1937

face coefficients of heat transfer. To use this method in the present case, the assumption is made that the film coefficient of heat transfer is some function of:

The cylinder, diameter D

The wind velocity V

The viscosity of air μ

The thermal conductivity of air K

The density of air ρ

and the specific heat of air C_p

That is:

$$H = \phi (D, V, \mu, \rho, K, C_p)$$

The unknown function may be expanded in terms of an exponential series:

$$H = A_1 (D^{a_1} V^{b_1} \mu^{c_1} K^{d_1} \rho^{e_1} C_p^{f_1}) + A_2 (D^{a_2} V^{b_2} \mu^{c_2} K^{d_2} \rho^{e_2} C^{f_2}) \ldots \quad (1)$$

Each of these terms is of the form:

$$A (D^{a} V^{b} \mu^{c} K^{d} \rho^{e} C_p^{f})$$

In which the d,b,c,d,e,f, are dimensionless constants. Each of the terms in the right hand side of this equation must have the same net dimensions as the terms in the left hand side of the equation.

Each of the variables may be expressed in terms of the five fundamental dimensions:

Mass - m

Time - T

Length - L

Temperature - t

Quantity of heat - Q

The dimension of the diameter is simply L. The dimensions of velocity is length per unit time or $\frac{L}{T}$. Of viscosity is $\frac{m}{LT}$. Of the density is $\frac{m}{L^3}$

Of the specific heat is $\frac{Q}{mt}$

Of thermal conductivity is $\frac{Q}{LTt}$

Equating the dimensions of the general term to the dimensions of h gives the equation:

$$\frac{Q}{L^2 T t} = L^a \left(\frac{L}{T}\right)^b \left(\frac{m}{LT}\right)^c \left(\frac{Q}{LTt}\right)^d \left(\frac{m}{L^3}\right)^e \left(\frac{Q}{mt}\right)^f$$

This relation is identical to

$$1 = m^{c+e-f} \; L^{a+b-c-d-3e+2} \; T^{-b-c-d+1} \; t^{-d-f+1} \; Q^{d+f-1}$$

which can only be satisfied if each of the exponents is equal to 0.

$c + e - f = 0$

$d + b - c - d - 3e + 2 = 0$

$-b - c - d + 1 = 0$

$-d - f + 1 = 0$

$d + f - 1 = 0$

These five simultaneous equations in six unknowns cannot be completely solved, but a, b, c, and d may be found in terms of e and f.

This solution is:

$a = -1 + e$

$b = e$

$c = -e + f$

$d = 1 - f$

The general term in the series then takes the form:

$$A D^{-1+e} V^e \mu^{-e+f} K^{1-f} \rho^e C_p^f$$

and equation (1) may be rewritten as:

$$\frac{HD}{K} = \sum A_n \left(\frac{DV\rho}{\mu}\right)^{e_n} \left(\frac{C_p\mu}{K}\right)^{f_n}$$

Recent studies have shown that $f_1 = f_2 = f_n = 0.3$ to 0.4 so for air the terms $\left(\frac{C_p\mu}{K}\right)^{f_n}$ may be considered constant and included in the value of the constants. A_n

Equation (1) then becomes:

$$\frac{HD}{K} = \sum A_a \left(\frac{DV\rho}{\mu}\right)^b$$

The term $\frac{HD}{K}$ is known as Nusselt's number and $\frac{DV\rho}{\mu}$ is called Reynold's number. McAdams has published a summary of the work of 13 different workers in the field of convective heat transfer and shows that the relation between these two numbers is a smooth continuous function.

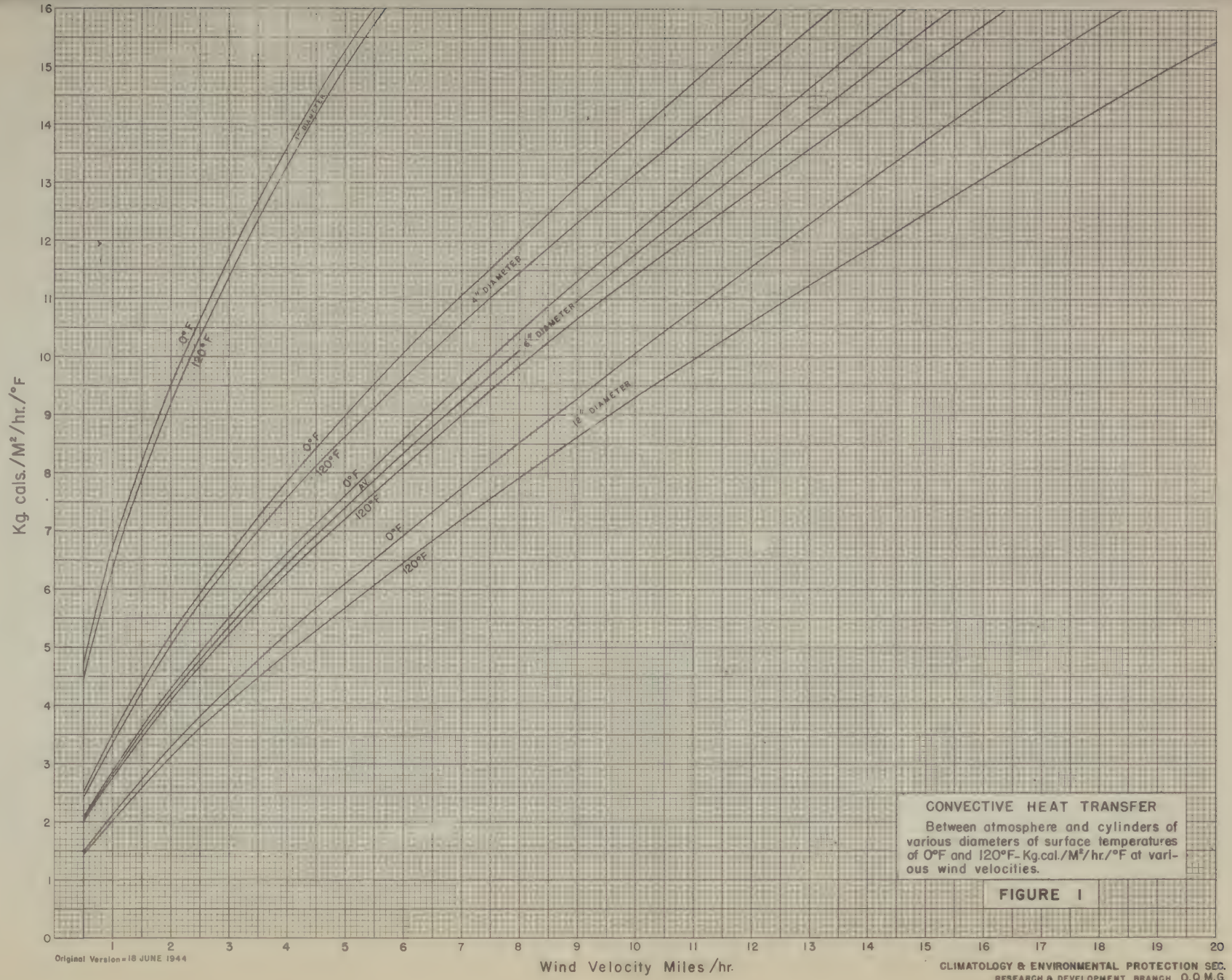
The equation:

$$(2) \qquad \frac{HD}{K} = 1 + .407 \left(\frac{DV\rho}{\mu}\right)^{\frac{1}{2}} + .00123 \left(\frac{DV\rho}{\mu}\right)$$

fits McAdams' curve with a maximum error of less than 5% between the values of Reynold's number 100 and 25,000. For the present purposes, this is the complete range since small values of Reynold's numbers occur only with very small diameters or extremely small wind velocities.

This equation is in the form which would be expected from dimensional analysis and consequently should very closely express the way in which surface coefficients are effected by such variables as wind velocity, temperature, and diameter of cylinder. Unfortunately, it is not a simple equation to work with, but it may be readily solved by graphical means.

Solving equation (2) in this way for diameters of 1, 4, 6, and 12 inches, and for temperatures of 0 and 120°F., a set of curves can be developed which show the relationship existing between convective heat transfer and wind velocity for various diameters and temperatures (Fig. 1). It is obvious that the diameter plays a very important part and also that the effects of temperature, while



CONVECTIVE HEAT TRANSFER

Between atmosphere and cylinders of various diameters of surface temperatures of 0°F and 120°F- Kg.cal./M²/hr./°F at various wind velocities.

FIGURE I

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STANDARD CROSS SECTION
ENGRAVING 320 SKS TO THE HALF INCH

appreciable, may be neglected in any but the most precise analysis. By taking a cross plot of this last set of curves and showing convective heat transfer as a function of diameter for specific values of the wind velocity, the effective diameter of the human body may be found from the work of Winslow, Herrington, and Gagge. The best agreement occurs when the diameter of the nude human body is chosen as 3 inches. Within the range of experimental wind velocities used by Winslow, Herrington, and Gagge, the points fit the 3 inch curve with an accuracy of approximately 2%. Upon extrapolating the physiological data to higher wind velocities, the difference may be of the order of 30%. Figure 2 shows the convective heat transfer and thermal resistance for cylinders of varying diameter, including the three inch. The result of temperature differences has here been averaged over the range likely to include the human body. Radiation is not included.

To compare this data with Burton's, a correction to the convective heat transfer must be added to account for the radiation lost from the surface. Assuming black body conditions, this is equivalent to adding a constant term of 2.65 kilogram calories per degree F. to the total convective loss. Upon converting the conductance to resistance in clo value, the agreement with Burton's data is reasonably good. In the range of wind velocities from $\frac{1}{2}$ mile per hour to 20 miles per hour, the deviation, in general, is only .05 clo or less. The maximum variation is found at $\frac{1}{2}$ mile per hour where the deviation rose to .08.

CONVECTIVE HEAT TRANSFER AND THERMAL RESISTANCE FOR CYLINDERS OF VARYING DIAMETERS

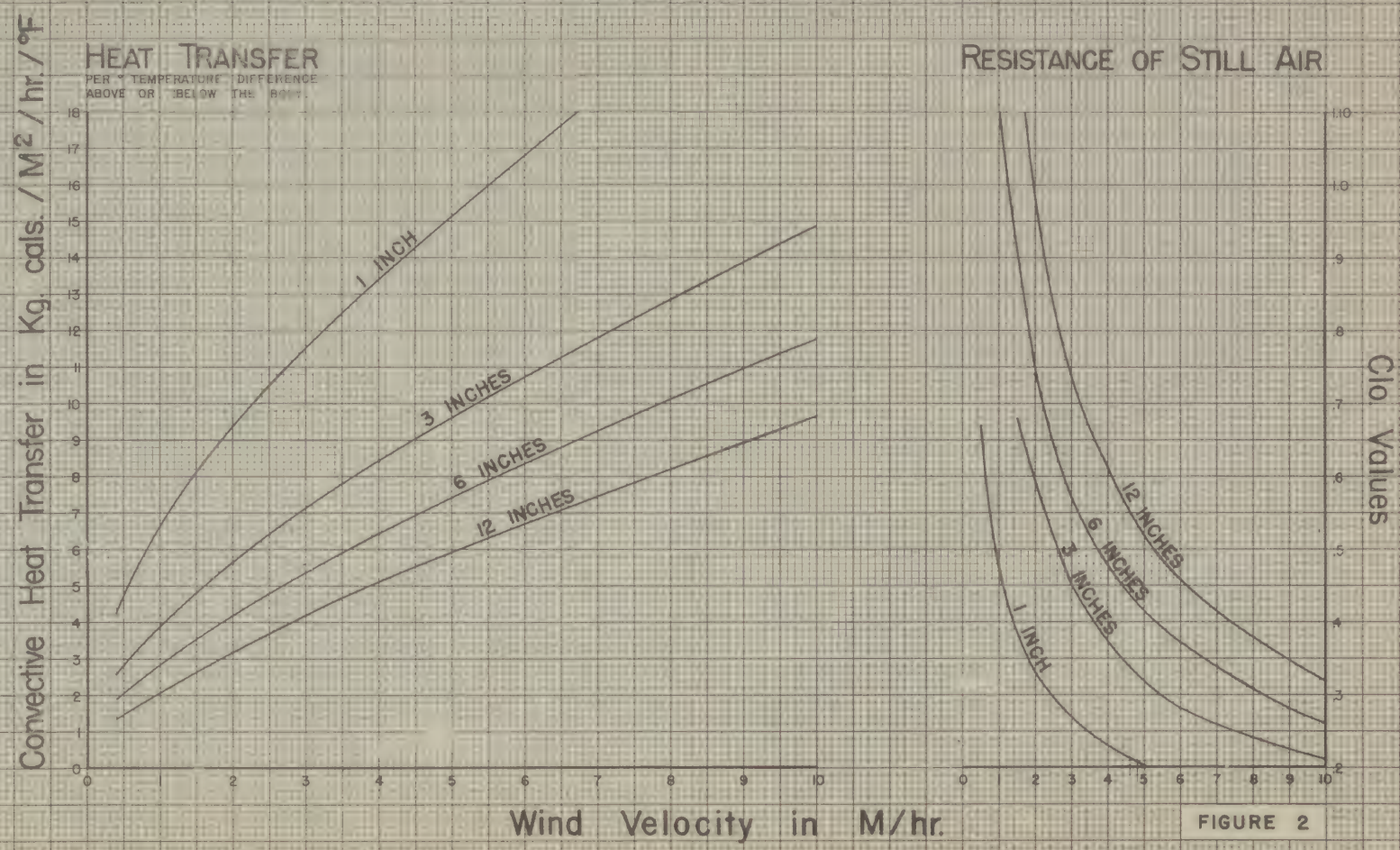

FIGURE 2

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DISCUSSION

DR. BURTON:- In some calculations I made in Toronto based only on my own dimensions, I found the average diameter to be 7 cm.

DR. PLUMMER:- I am glad you mentioned that for the value of 3 inches we found was so small that we were rather disturbed about it.

DR. THOM:- May I make a comment? In some experiments we made, the radiation factors were extremely important. It probably will be much more important in the human body because of the difference in temperature between the body and the outside air. When the gradient between the body and the air is increased, the radiation factor must be altered.

DR. PLUMMER:- This is perfectly correct, but for a limited temperature range, the radiation factor may be considered constant without introducing an appreciable error.

DR. BURTON:- In a recent conference here on standardization of methods, I showed that, with a change in external temperature from 70°F. to -40°F, the change in the radiation factor is almost exactly compensated for by the change in convection. I think that we may take a standard curve and neglect the effect of temperature for all practical purposes. Do you agree?

DR. PLUMMER:- I do. Certainly the error involved is less than the experimental error in practical measurements.

COL. HATCH:- The present discussion concerns only transverse air flow. As the transverse velocity is diminished, a longitudinal velocity, caused by the temperature difference between the body and the air, will begin to be effective. At what transverse velocity does the

vertical movement cause a change in the results, and how can you combine the effect of the two velocities?

DR. PLUMMER:- Only additional experiments could provide a complete answer. Equation 6 is valid for transverse velocities as low as 0.1 miles per hour. Below this, it departs appreciably. Since we are primarily interested in outdoor conditions, lower velocities were not considered. I believe that the effect of the transverse velocity is 10 to 12 feet per minute or less.

CONDUCTIVE HEAT TRANSFER AND CLO VALUES

Dr. Plummer then introduced Mrs. Margaret Ionides Cochran.

MRS. COCHRAN:- For the benefit of our visitors who may be more or less unfamiliar with the scientific study of clothing, I should like to define a clo unit. The clo unit* was first described by Drs. Gagge, Burton, and Bazett in an article in "Science" in 1939. A clo serves the purpose of establishing a unit of insulation for the human body which can be used by physiologists, clothing experts and housing engineers. It is a resistance unit similar to an ohm in electricity. One clo is defined as the amount of clothing necessary to keep a man comfortable at normal indoor winter conditions, or, to be more precise, at a temperature of 70°F with relative humidity less than 50% and almost still air. The number of clo necessary for any other condition varies with the amount of heat which the man's body is creating, the temperature of the outside air, and the wind velocity.

In laboratories when clo measurements are taken, the metabolic rate of the man is gauged by determining the heat lost from

*See Appendix 2

the skin, the amount of heat lost by warming the air which the man breaths, and the amount of heat lost by evaporation from the skin surface and from the lungs.

Since the clo is a physical unit of heat resistance, the value of clothing may be determined by a simple calculation; measuring the thicknesses, calculating the resistances, and adding them.

This method is illustrated by these two charts, Figure 3, "Combat Uniform 3 Clo", and Figure 4, "Arctic Uniform 4 Clo". We call these the thickness charts. I should like to point out that these particular charts are more an illustration of method than a statistical analysis of the way in which clothing fits various subjects. Only one or two men were measured in making these charts.

Very careful measurements were taken of the circumference of a man in the nude, and at each stage of his dressing. These circumferences were then converted to radii. The difference between the nude radius and the clothing radii gave the thickness of the layers plus the included air at each stage. The textiles were also measured for their thickness by a precise instrument. Two thicknesses were taken for each material; (1) the greatest possible thickness without any pressure, and (2) the thickness at 1 pound per square inch of pressure. (Occasionally arbitrary adjustments were necessary to take into consideration the extra thickness of pockets, binding, and findings.)

In construction of the graph, we measured first the full radius of the outside layer since this was the absolute maximum

ARCTIC UNIFORM — 4 CLO

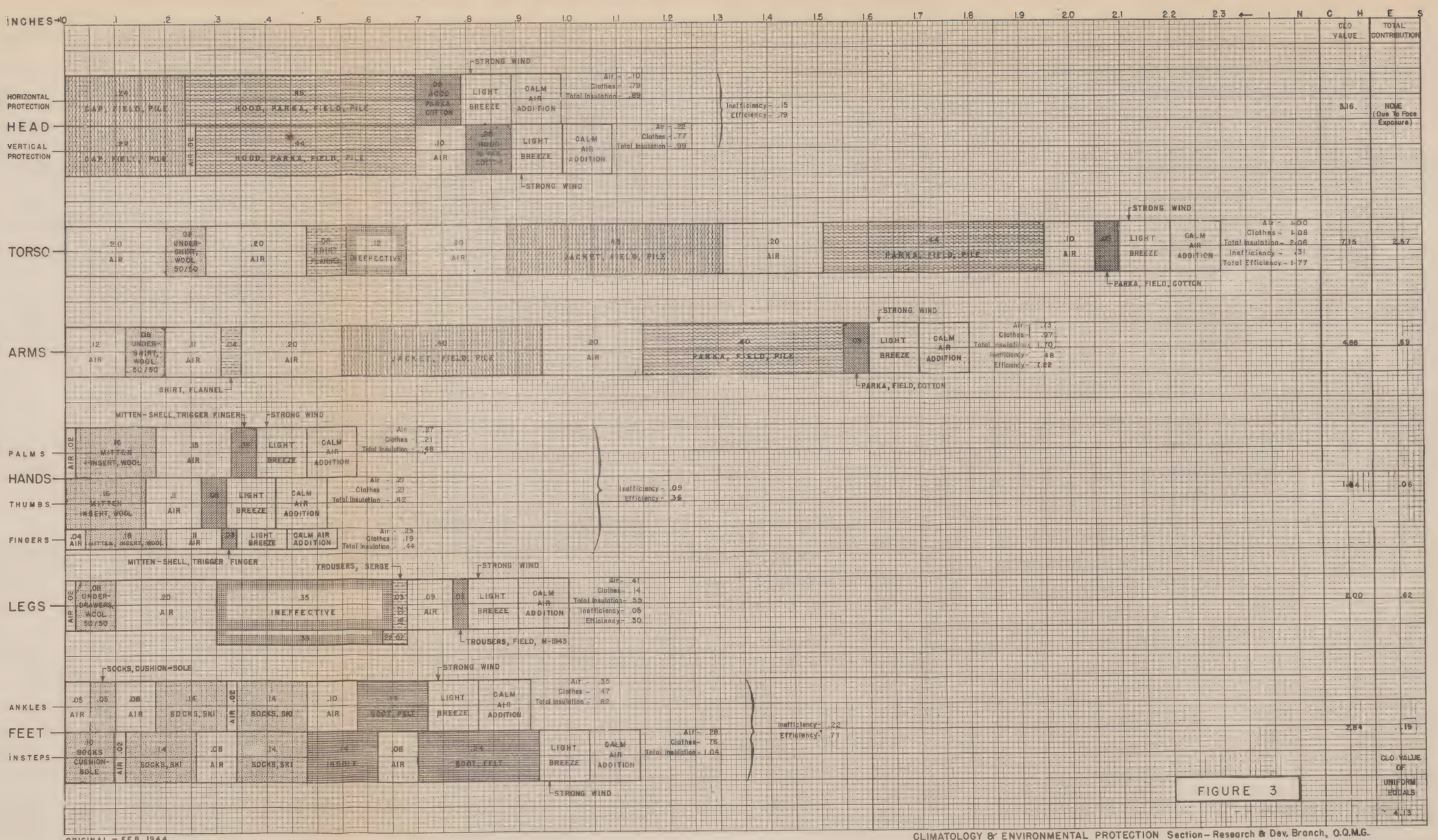

FIGURE 3

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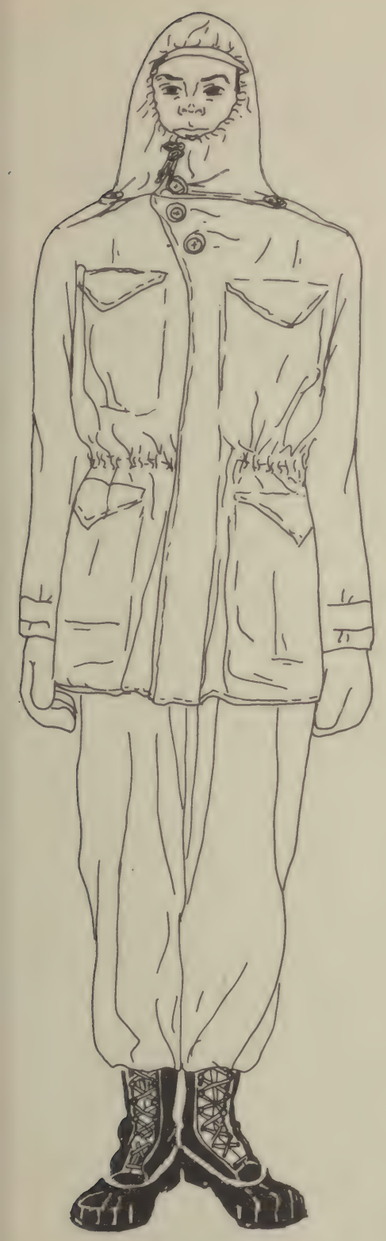
34-28286-300

COMBAT UNIFORM — 3 CLO



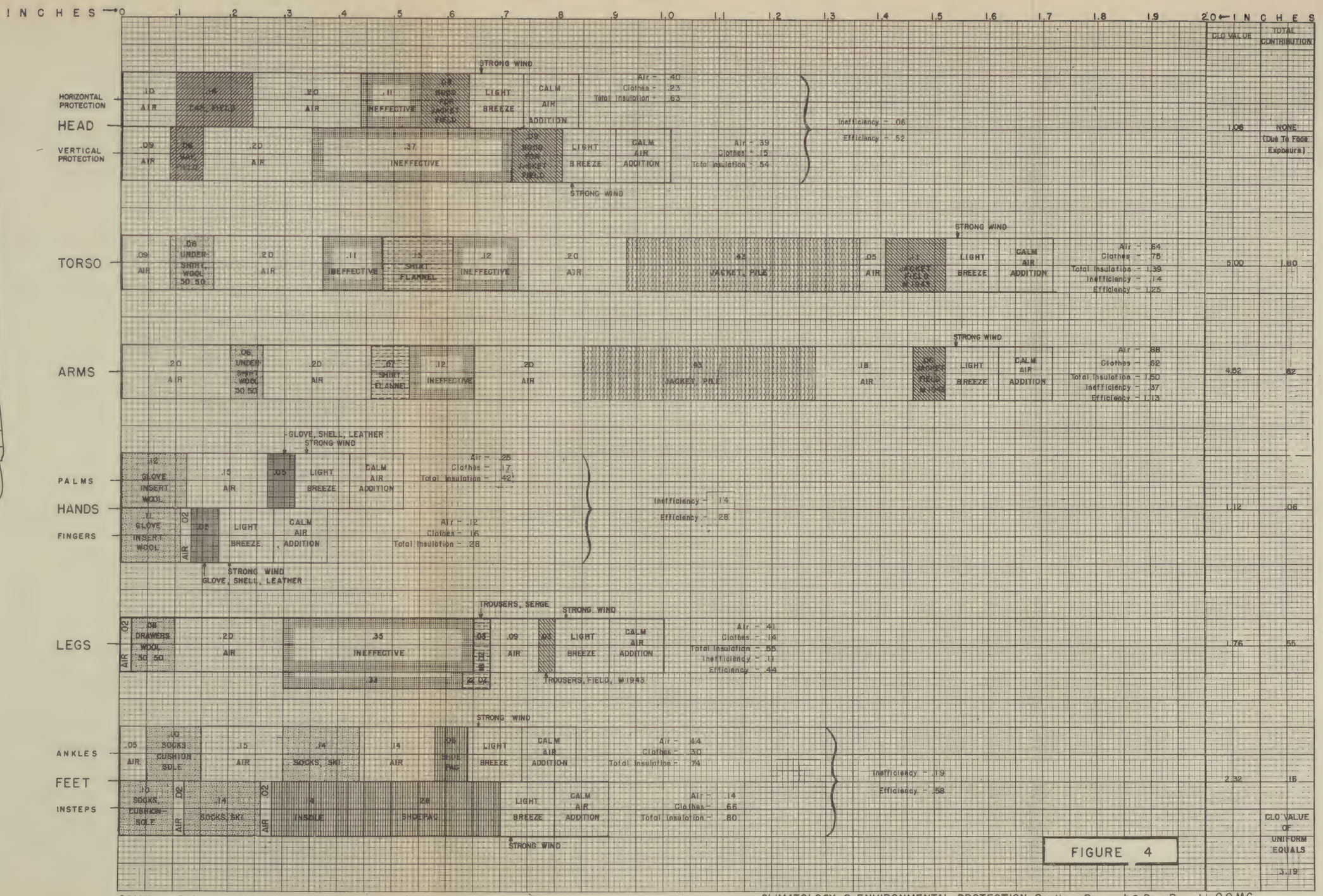


FIGURE 4

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of the thickness of the clothing. The difference between this outermost radius and the radius of the next layer of material represents the space available for the textile plus the included air. When the space between layers was smaller than the optimum thickness of the clothing, then compression was apparent at some point beneath. If the space were greater than the possible thickness of the material, it was obvious that the full benefit of the insulating value of the material was present plus the amount of dead air for which there was room. (If this dead air between layers exceeded .2 of an inch, the additional air was judged to be inefficient, since above that amount convection currents will set in and reduce the insulating power of the air. For example, notice the large inefficient spaces of the trouser legs.)

When the bar graph for each part of the body was finished, the total efficient thickness of air and clothing was added together. One-fourth inch of air and material is approximately equal to one clo. This gives the clo value which would be present if the material and air were covering a flat plate.

After the diagram was complete, two corrections had to be made in estimating the adequacy of the clothing. The first was the correction for insulation loss due to the increase in surface area provided by the varying sized cylinders. This is a form of the law of diminishing returns. Extra clothing layers cannot give proportionally greater insulation. If a small stove is put in a small storeroom, it will heat the room sufficiently. If, however, it is put in a large circular storeroom, the room

will not be heated even though it is filled to the ceiling with soft wool. This is because the radiating surface from which the heat is lost increases more rapidly in proportion to the radius of the insulation.

The same is true in the body. As extra layers are added, the area of their surface increases. This is obvious when one realizes how much more material is needed to make a shirt than an undershirt and how much more still to make a coat. As a result of this increasing size, the efficiency of each additional layer is decreased.

The smaller the cylinder, the more rapidly the surface area increases in proportion to the square of radius and the greater the decrease of efficiency as additional layers are added. Figure No. 5 shows the relationship of effective insulation to surface area. Two and one-half inches of insulation around the torso would be 80% efficient; whereas, the same over the hands would be only 40% efficient, besides being impractical for dexterity. These corrections for surface area are shown as the efficiency and inefficiency figures on the charts. This gives the figures listed in the column under clo values, which represent the local insulation provided for each part of the body.

The second correction made is due to the varying loss of heat from different parts of the body.* The feet, for example, lose only 7% of the total body heat while the torso loses 36%. The value of the weighted figures is shown in the column under total contribution.

If should be noted that the clothing indicated here gives

*See Appendix 3

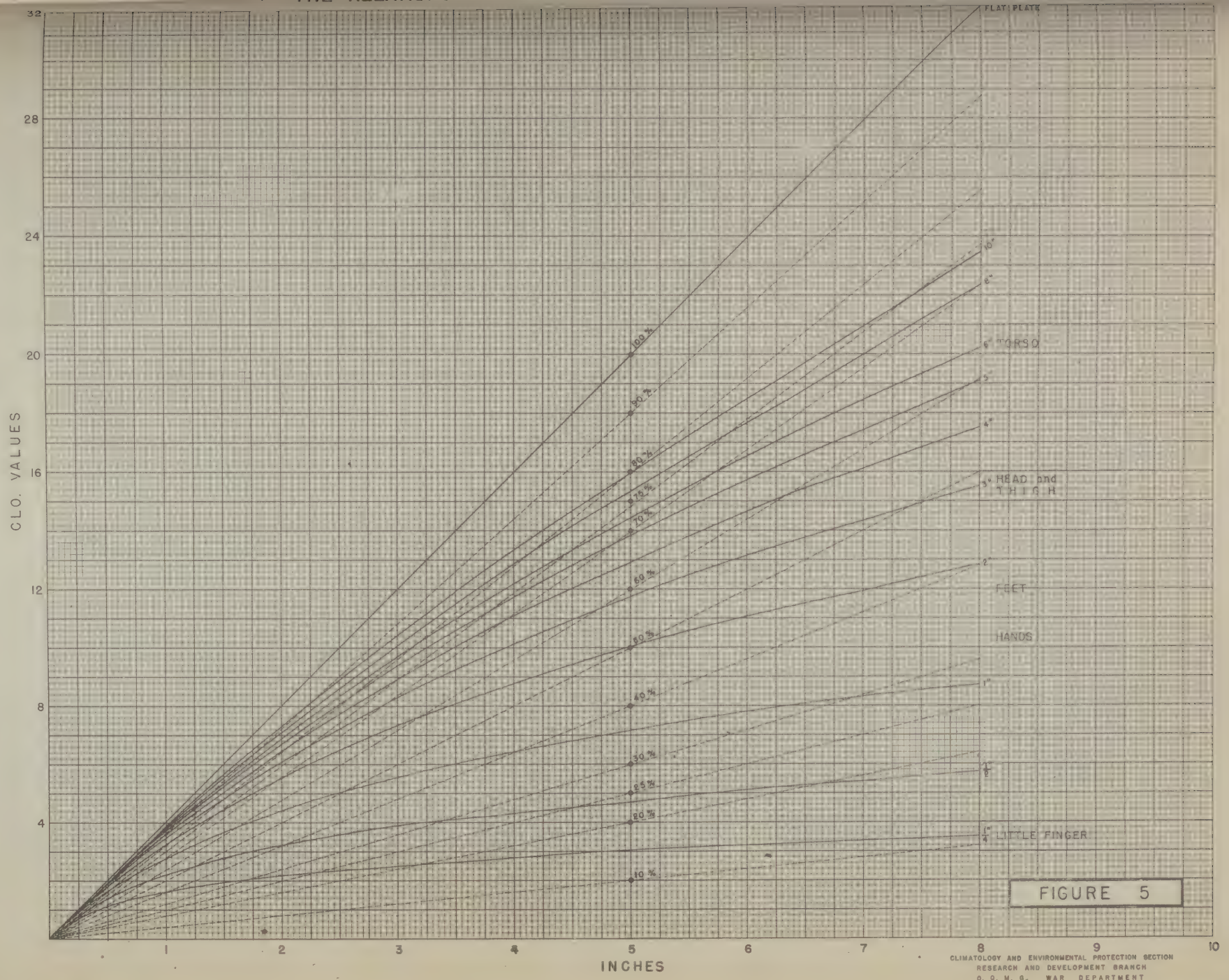

FIGURE 5

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fairly adequate protection for all parts of the body, except for the face. Very different effects will be found if any portion of the body is inadequately protected.

The final column of figures is the contribution which the clothing over each part of the body makes as the whole. Laboratory measurements have shown the arctic uniform to be approximately 4 clo. When the figures in the final column are added, it will be seen that with the measurement of thicknesses, the uniform appears to be 4.13 clo. In the same way, the laboratory 3 clo uniform is calculated to be 3.19 clo.

A greater variation than this between laboratory measurements of conductance and these calculations of resistance might, of course, be expected to occur if measurements were made on more subjects.

By means of this method of estimating clothing insulation as an alternate to precise physiological tests, a number of advantages are obtained other than its short cut measurements. Some of the advantages over cold chamber metabolic clo testing are as follows:

(a) To make a quick and simple estimate of the insulation value which any garment contributes to a given assembly.

(b) To determine the thermal balance of an assembly of clothing for the purpose of correcting points which are too tight or too loose to give optimum protection. Also to indicate where additional thickness may be added to improve insulation with a minimum increase in weight.

(c) To evaluate the loss of local insulation at pressure points.

(d) To evaluate the component parts of lined garments.

(e) To provide a suitable means of making a measurement analysis of a large group of soldiers to determine the adequacy of garment sizing.

It is suggested that the application of this method might bring to light other interesting differences in insulation such as is provided by the front and back of the jackets due to the presence of numberous pockets and findings.

In order to use the clo values for an index, it is necessary to correlate them with climatic conditions. Figure No. 6 "Clo Values" shows the temperature along the side and the activity or the heat produced by the body across the top. This chart is plotted for an average wind of 5 miles an hour. From it, one may determine what clo is necessary to keep a man in thermal equilibrium for various activities between sleeping and marching at 4 miles per hour at any given temperature if the clothing and atmosphere are dry. For use in the index, it seems probable that the best activity to select would be one which would cover such activities as truck driving, standing at guard duty, and standing with occasional shifting of feet. Naturally, if this man begins to walk fast, he will have to remove some layers of his clothing; nevertheless, it is far more necessary that he be well protected at a low activity than at a high. If he is forced to lie still in a fox hole with this clothing, his endurance will be limited by a time factor; although lack of wind will give him considerable added protection.

The range of activities cited here (between 65 and 75 Kg.Cals/M^2/hr) has the additional advantage in that they can be

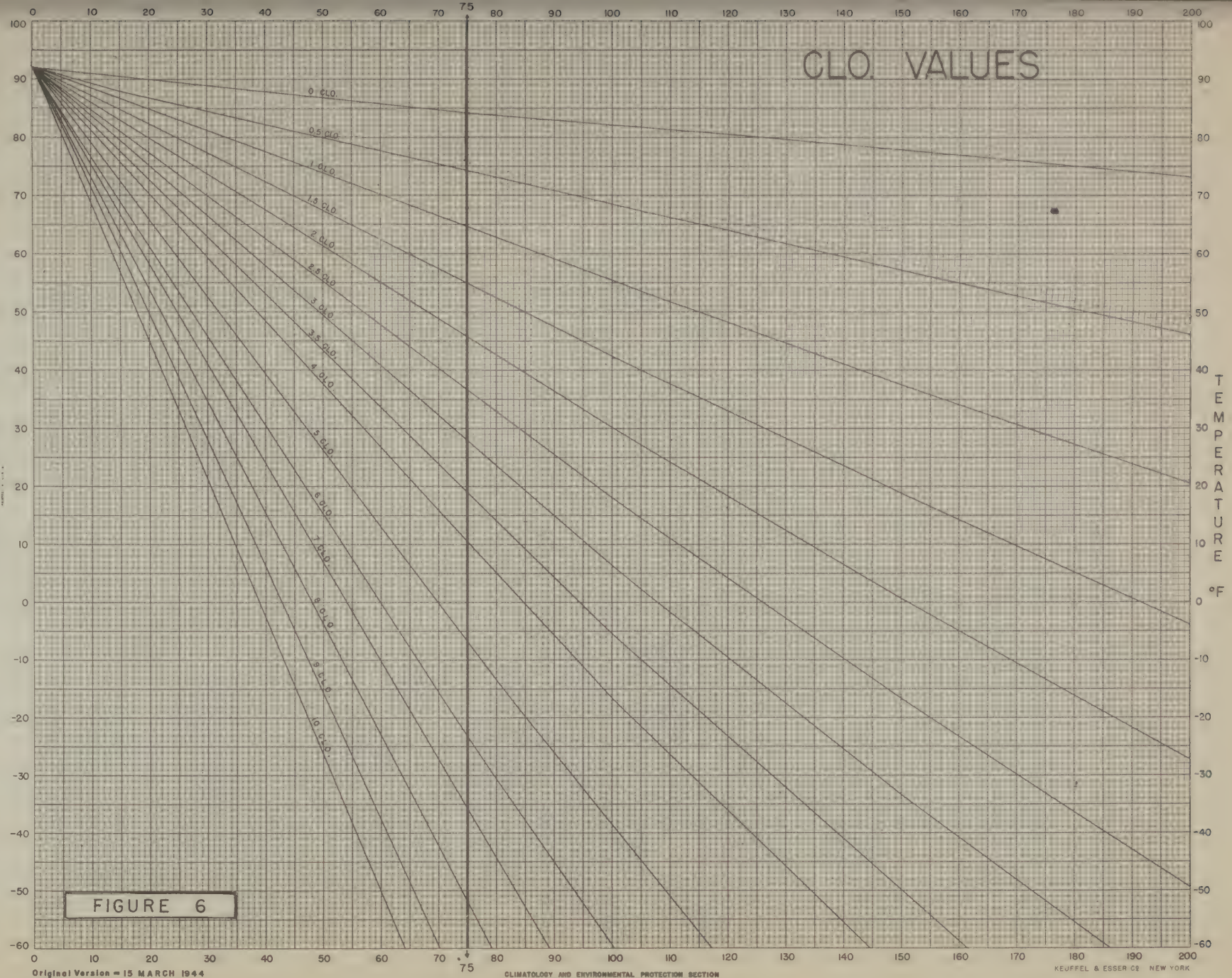

FIGURE 6

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correlated with the Climatic Zone Maps. In this range, one additional half clo is needed for each 9°F drop in average air temperature. The Climatic Zone Maps are so designed that the temperature range of each zone is 18°F or 10°C. For precise purposes of clothing distribution, half clo lines should also be drawn on the 9°F temperature lines.

DISCUSSION

DR. BURTON:- An extension* of the report on limits of thermal insulation (Climatic Research Laboratory, Report No. 76) might be made to include the effect of increasing surface area on total insulation of the air, as well as of the clothing. This shows the limitations of insulation on surfaces of small radii of curvature to be even more drastic than has been supposed. Unless the outside diameter exceeds a certain value, adding an insulation layer may even increase, rather than decrease, the heat loss. This critical condition could hold for the fingers in very still air. It is possible that thin gloves of poor insulating material actually made the hands colder. This idea never applies to handgear in greater air movements. For precise measurements, account should be taken of this connection in clo determination on gloves, and caution should be taken not to interpret results in hand calorimeters, with very still air, as indicating the practical usefulness of thin inner gloves in the field. The importance of

*This discussion is now published in N.R.C. Canada, S.P.C. Report No. 174.

using the best possible insulating material (such as Aerogel) for handgear should be emphasized.

DR. BELDING:- I feel that the Clo value charts issued by this section must be used rather cautiously. They are probably quite accurate for low activity rates, but when the rates of work become high, sweating occurs, at least localized sweating, and the evaporative heat loss must be taken into consideration. This has not been done in the present tolerance time figures.

DR. PLUMMER:- You are quite correct, we have not taken into account the evaporative heat losses in calculating tolerance times regardless of the rates of activity. We would like to do so, but unfortunately have had no data which we could use for this purpose. In spite of this, however, we think that the tolerance times as calculated at present are a reasonably good approximation and are somewhat on the conservative side because they are based on a total loss of 40 or 80 Kg. Cal. per square meters.

Local sweating is primarily an unbalanced situation, i.e., one portion of the body is generating more heat than necessary and other parts of the body are probably generating less heat. We would very much like to have some information concerning the quantity of heat output per unit area for different parts of the body as a function of the activity. This would give us information with which to calculate the effects of unbalanced clothing conditions, and it would also permit us to take into consideration the evaporative heat loss and then the calculation of tolerance times.

DR. BELDING:- Of course, the clo equation cannot be taken with great precision. In applying the equation which Burton originated to human subjects, we have found that there is a variation of 10 to 15% between different subjects on the same day and also between the same subjects on different days. This whole matter is discussed in a revised edition of the Harvard Fatigue Report No. 19, dated 3 August 1944.

DR. BURTON:- Is it not possible that some of this variation is due to the way that the clothes fit?

MAJOR SIPLE:- In the early stages of this work two years ago, many physiologists believe that any type of clothing index would be impractical because of the great difference between human beings. Further study of the factors governing heat loss shows that many of these variables are external. The same man may not put on his clothes in just the same way two days in succession, and the same clothes will not fit two different men just alike; as a result, there will be considerable variation in the distribution of dead air space and pressure points from time to time.

MRS. COCHRAN:- In report No. 76 from the Climatic Research Laboratory to which Dr. Burton referred, the clo value per inch was taken as the maximum for dead air space. This value is, I believe, 4.7 clo to the inch. However, I should like to ask Dr. Burton whether with the inclusion of textiles this figure would not drop to about 4 clo to the inch?

DR. BURTON:- 4 clo per inch seems to me an acceptable estimate. It is the value we take for calculations of dead air and clothing.

EVAPORATION

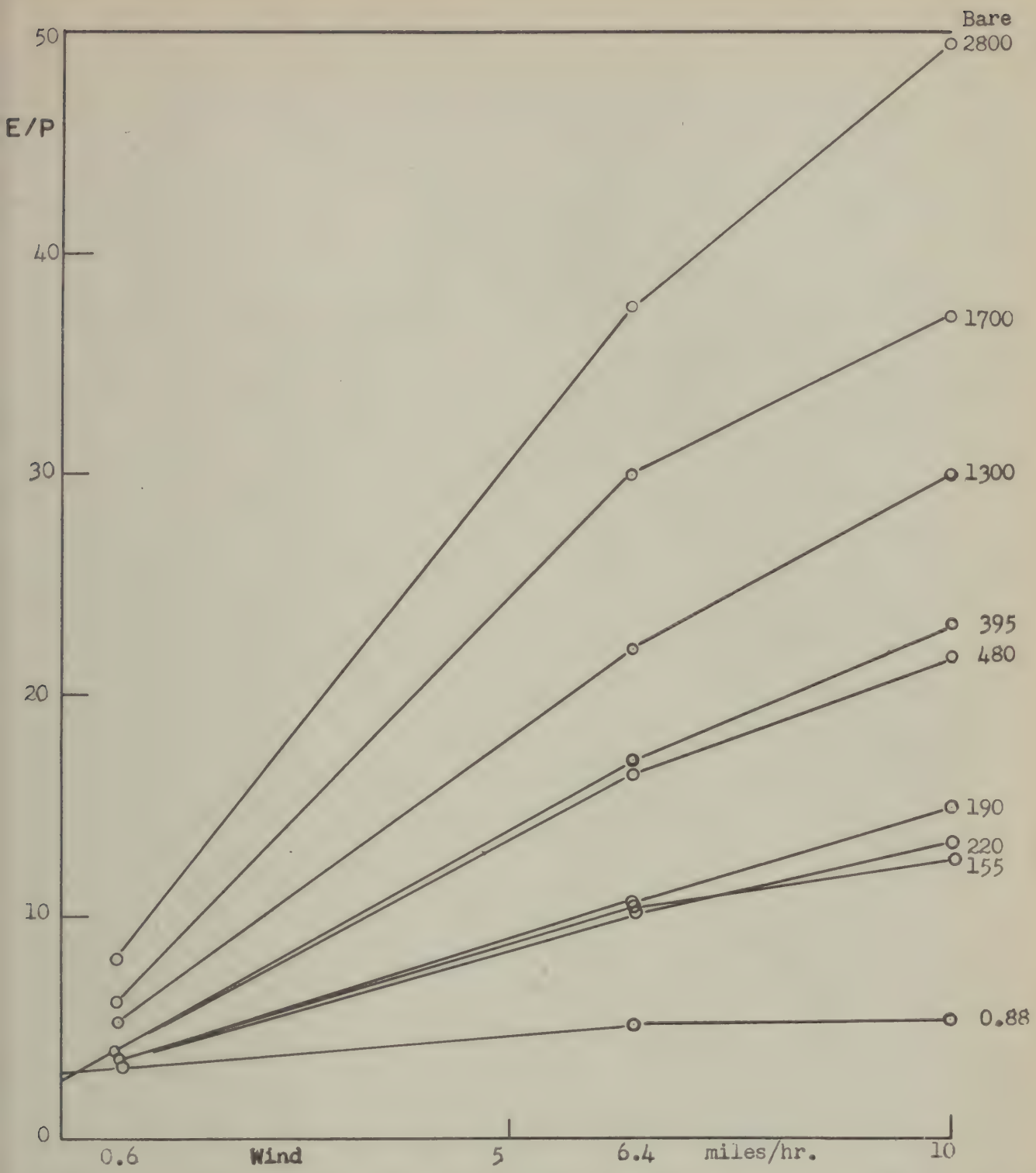
Dr. Plummer then introduced Dr. Fourt of the Bureau of Standards to speak on the subject of "Evaporation".

DR. FOURT:- We tried two different kinds of experiments at Dr. Plummer's request. The first of these concerned the effect of wind on the evaporation from a completely wet cylinder. The observed rates of evaporative cooling are shown on Figure 7 in Kg.Cals/M^2/hr - (E) per millimeter vapor pressure difference, (P) are plotted against wind speed (V) in miles per hour. The upper curve shows the results for a wet surface without any cover. It is distinctly curved, rather than linear with wind velocity. Powell* studied the evaporation from completely wet cylinders of different diameters, in air streams of different speeds. These are shown in Figure 8. His equation may be written:

$$E/P = \frac{35.1\ V^{.6}}{D^{.4}}$$

When D is the diameter in centimeters. For the diameter of the

*Trans. Inst. Chem. Eng., 18, 36 (1940).



Relationship of evaporation rate to wind velocity, for fabrics having the air permeabilities shown at the ends of the lines. E/P = Kg.cal/M^2 per mm. vapor pressure difference. Air permeability = ft^3/ft^2 min at pressure = 0.5 inch water.

FIGURE 7

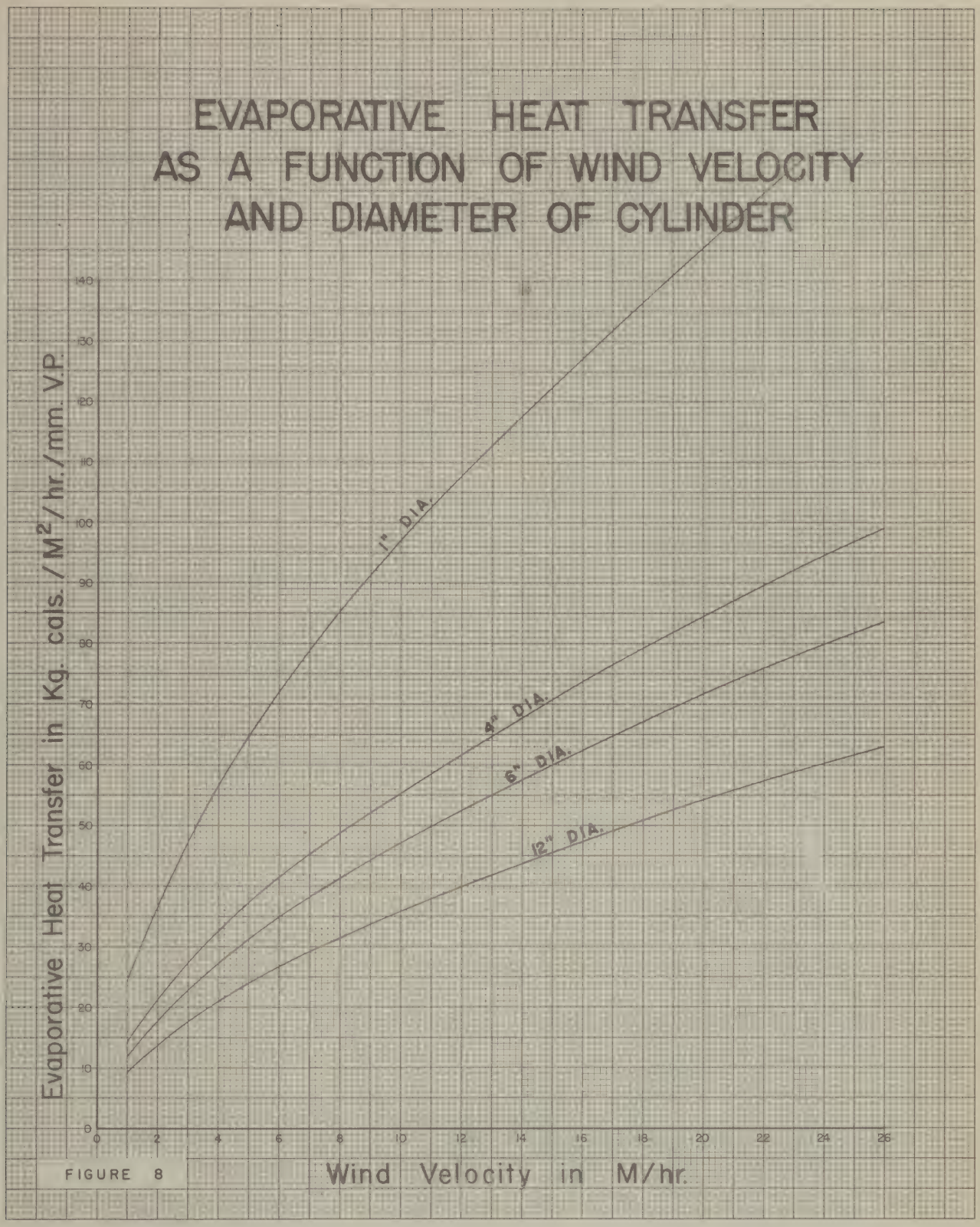


FIGURE 8

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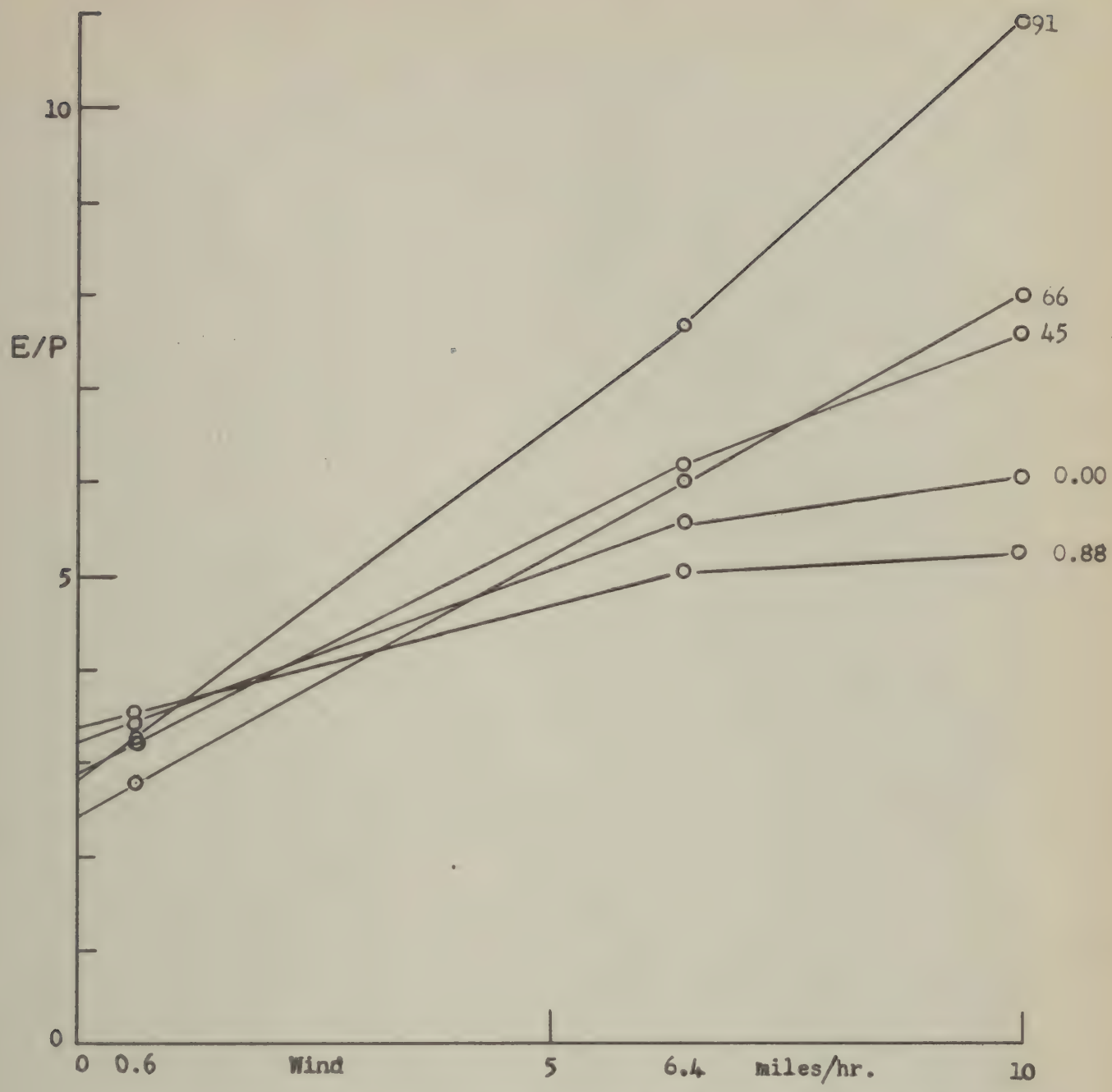
artificial sweating man, 20.4 centimeters, this reduces to -

$$E/P = 10.5\ V^{.6}$$

The observations at the higher speeds lie 15% above Powell's values but follow the same general trend. Perfect agreement should not be expected, because Powell was concerned only with the sides of the cylinders, while these experiments included evaporation from the flat top.

Gagge, Herrington and Winslow, American Journal of Hygiene, 26, 84 (1937) have given a different type of equation for the effect of air movement on evaporative cooling from a man with completely wet skin, which may be written $E/P = 2.8 + 1.0\ V$. This may apply better than Powell's at low air movement, since it includes the effect of natural convection, but it falls 75% too low at 10 miles per hour.

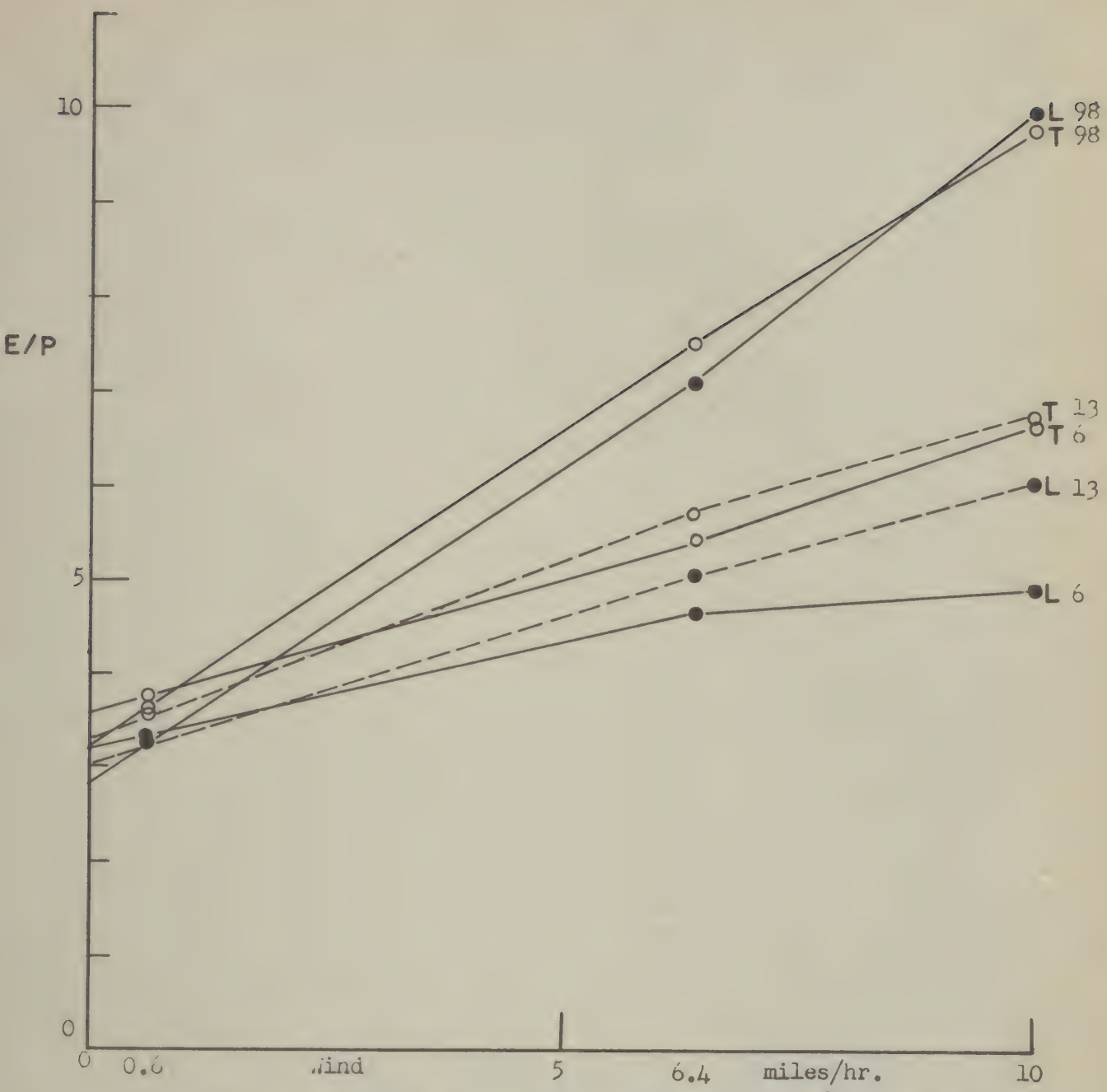
The other type of experiment which we have done concerns the evaporation from a wet skin through dry clothing. A cylindrical fabric cover was held at an average distance of 0.7 centimeter from the wet blotting paper. Under these conditions, the rate of evaporation depends on the air permeability of the fabric, as shown in the charts (Figure 9). Air permeability is expressed in cubic feet of air passing through 1 square foot of fabric per minute, at a pressure difference across the fabric equal to 0.5 inch water. In addition to air permeability, the size of the cover, or the amount of air trapped between cover and skin makes a difference, as shown in the chart (Figure 10). For any fabrics of low permeability, such as herringbone twill or poplin, these size factors are of as much influence as the permeability factor.



Effect of wind on evaporation (E/P = kg cal/m^2 hr per mm vapor pressure difference).

Fabric	Air Permeability
Palm Beach	91
Coat + shirt + underwear	66
6 oz. khaki	45
JO cloth	0.88
Water permeable cellophane	0.00

FIGURE 9



Effect of wind on evaporation (E/P = Kg cal/m^2 hr per mm vapor pressure difference) for covers differing in size.

Material	Air Permeability ft^3/ft^2 min at 0.5 in water	Tight Radius cm	Loose Radius cm
Muslin	98	11.0	11.8
Herringbone twill	13	11.3	11.9
Poplin	6	11.0	12.2

FIGURE 10

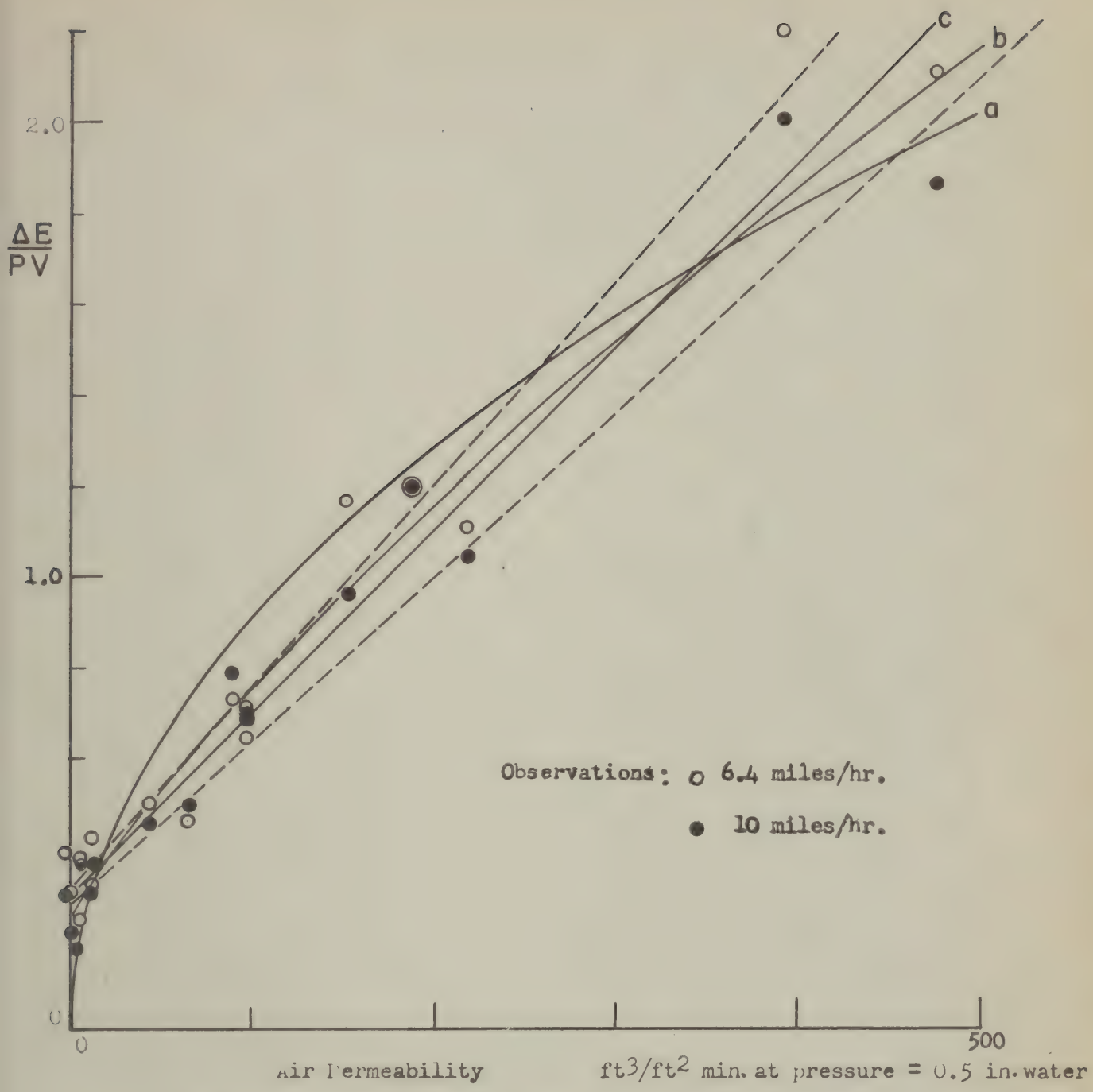
The combined effect of wind and air permeability can be analyzed in an empirical way, for the range of air speeds up to 10 miles per hour, and fabric permeabilities up to 500, neglecting small variations in size. The chart (Figure 11) shows the increase in evaporation per unit wind speed, plotted against air permeability of fabric. Various empirical relations can be fitted to this, but the one of present choice is a linear relationship which does not go through the origin. The fact that there is an increase in evaporation with increasing wind, even with zero air permeability, should be expected, since part of the resistance to evaporation lies in the air outside the fabric. The equation for the combined effects of air movement and fabric permeability is

$$E/P = 3 + (0.3 + .004\ A)\ V$$

in which A is the air permeability. The charts show that the experimental uncertainty is such that a difference in air permeability of about 30 is needed to demonstrate a difference between fabrics.

For the purpose of mapping the effect of climatic factors, it must be remembered that there is a big difference between the rates of evaporation from bare, wet skin and from clothed skin. The differences between these physical experiments and the reactions of a real man should also be pointed out. The physical experiments deal with a 100% wet cylinder, or with this covered by dry clothing. It is very seldom that the extreme condition of 100% wet skin is reached. Experiments at the Pierce Laboratory* have shown that the sensation

*Winslow, Herrington, & Gagge, A.S.H.V.E. Transactions, 44, 179 (1939)



Empirical equations connecting increase in evaporation per unit wind speed ($\Delta E/PV$ = Kg cal/m^2 hr per mm. v.p. difference per mile/hr. wind) with air permeability, A.

Line a is for $\Delta E/PV = 0.09\ A^{0.5}$
Line b is for $\Delta E/PV = 0.25\ (A/30 + 1)^{0.75}$
Line c is for $\Delta E/PV = 0.3\ (A/75 + 1) = 0.3 + 0.004\ A$
Broken lines indicate 10% deviation from line c.

FIGURE 11

of discomfort increases with increase in wetted area, and that above 75% wetted area is unpleasant. However, the clothing does not remain perfectly dry, and, since wet clothing resembles wet skin in rate of evaporative cooling, a real man presents a situation intermediate between the perfectly wet surface and the wet surface covered by dry clothing. These experiments show that the extreme cases can be described by two different types of equations: for wet skin or wet clothing, Powell's equation; for dry clothing, a modified form of Gagge's equation.

DISCUSSION

DR. BURTON:- The systematization of the information regarding evaporation from the body is in a manner analogous to the system of Clo units for thermal insulation. It is not necessary to invent a new unit other than that already used by Dr. Goodings and by Dr. Fourt, namely, the "equivalent centimeters of dead air". Incidentially, I suggest that "dead air" be used instead of "still air" to avoid confusion with the use of "still air" to denote that in a room without ventilation. Here convection currents make it very far from the "dead air" in a fabric or in the small dish of the experimental measurements. The fundamental equation of vapor transfer is:

$$\text{Cals/Sq.M./Hr. by evaporation} = \frac{(P_1 - P_a)}{R} \times 5$$

Where P_1 and P_2 are the vapor pressures of the skin and outside air in millimeters of Hg. and R is the resistance to passage of vapor in cms of dead air. By a fortunate coincidence, it turns out that in normal indoor conditions with normal clothing, the total resistance

R is about 1.7 cms of dead air. Of this, about 1 cm. is in the clothing, and 0.7 cms. in the outside air. In a wind the latter may fall to as low as 0.2 cms. The analogy with the thermal insulation normal clothing in clo units is complete. It is to be noted that a total up to 17 cms. of resistance to vapor could be tolerated before the inactive subject became uncomfortable. This indicated how far one could go with a protection impermeable suit before it became uncomfortable.

DR. PLUMMER:- Thank you Dr. Burton. We had not thought of calculating thermal transfer by vapor pressures in terms of resistance. That is a most useful addition.

We are most grateful to Dr. Fourt of the Textile Foundation for the assistance he has given us in studying evaporation. For including the evaporative heat transfer in the index, we suggest the graph as illustrated in Figure 12. The upper curved line on this graph shows the heat transfer from any bare surface irrespective of whether that surface is the nude skin or the clothing surface so long as it is entirely wet. Heat transfer can then be measured in Kg.Cals/M^2/hr. per millimeter vapor pressure difference between the surface and the atmosphere for any wind velocity. This corresponds to the upper curved line as shown in Dr. Fourt's diagram, Figure No. 7. For zero wind velocity, this also corresponds to the experiments made by Winslow, Herrington, and Gagge. When the figures taken from this line have been added to or subtracted from the corresponding figures for convection for any given atmospheric condition, the result should be the limits of safe activity which a man can endure without

storing additional bodily heat.

It is obvious, however, that men often become distinctly uncomfortable long before they have reached the limits of safe activity. Winslow, Herrington, and Gagge* have measured these limits of comfort in terms of percent of wetted area of the human body. Using a fabric of low air permeability such as Herringbone twill and replotting from the graphs shown by Dr. Fourt, we have drawn three straight lines near the bottom of the chart, No. 12. Reading from top to bottom, these represent respectively (a) 100% wetted skin surface covered with one dry layer of herringbone twill, (b) 75% wetted skin surface covered with one layer of dry herringbone twill, (c) 25% wetted skin surface covered with one layer of dry herringbone twill. Summer underclothes are included in the normal costume, the permeability of the material is sufficiently high to make no difference in the transfer factors.

For the purpose of demarkating efficient military service it may be necessary to plot 2 lines for every hot climate; one with the limits of safe activity, and another with a 75% wetted area or an extremely unpleasant line, since in some climates extreme unpleasantness and hence decrease of efficiency is apparent under normal daytime conditions even though the threshold of danger rarely occurs, whereas in other climates unpleasant conditions may be reached at a temperature and vapor pressure only slightly below those of critical danger.

Until the limits of danger are reached, there will be, of course, a considerable time when the body is not all wet nor the clothing all

*Reprint from The American Journal of Hygiene, Vol. 26, No. 1, 103-115, July, 1937.

dry. Adjustments for these periods could be made but since their variations are so numberous, it seemed more reasonable to make the estimates which we have shown.

These then are our suggestions for the evaporation factors to be included in the index.

The meeting was adjoined for lunch at 1300 hours.

EVAPORATIVE HEAT TRANSFER AS A FUNCTION OF WIND VELOCITY, SURFACE COVERING, AND WETTED AREA FOR AVERAGE HUMAN BODY

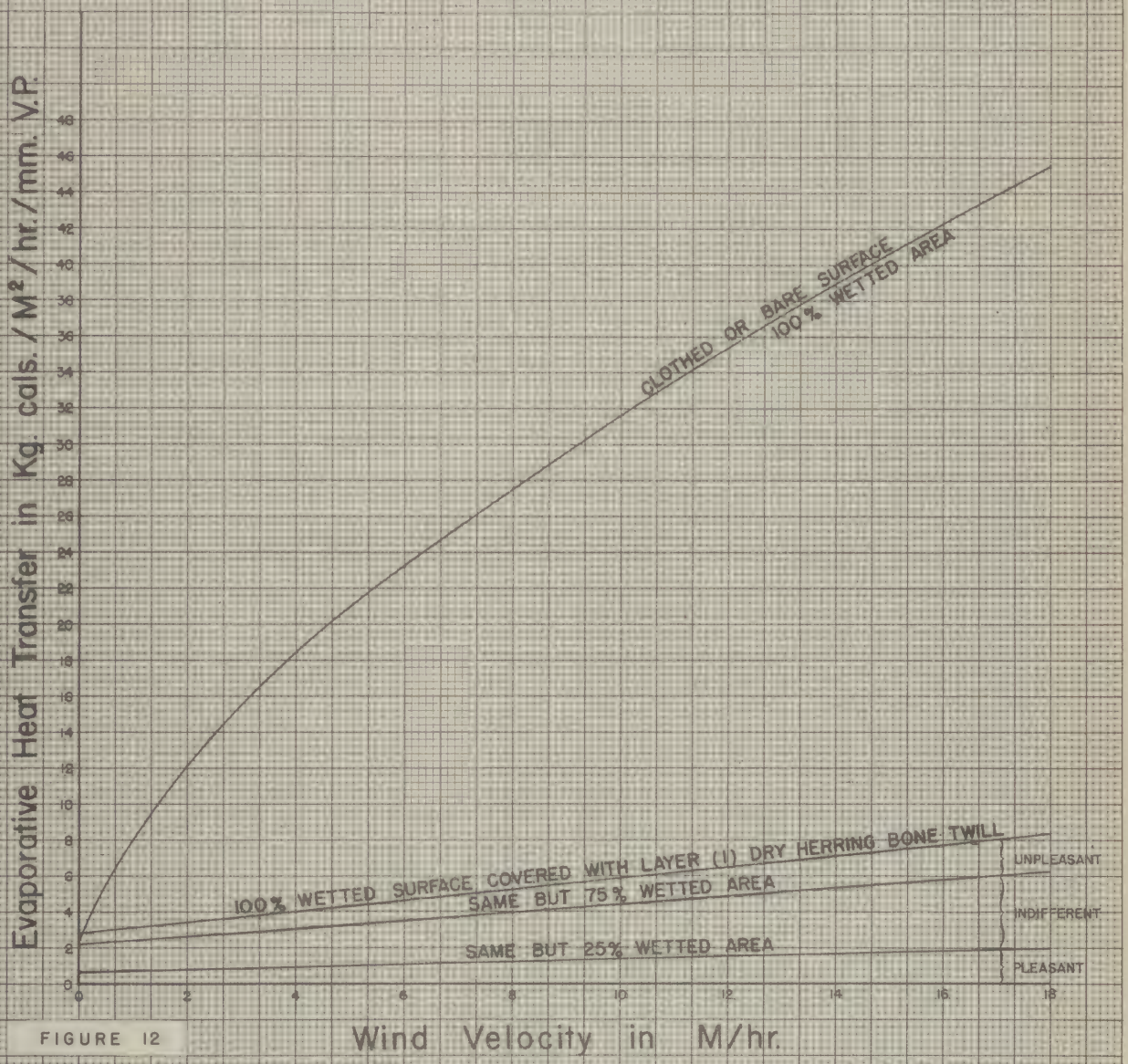


FIGURE 12

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The meeting was reconvened by Major Siple at 1430 hours.

Dr. Plummer then introduced Mrs. Elizabeth Schickele.

RADIATION

MRS. SCHICKELE:- In considering radiation, particularly out-of-doors, we discover that radiation exchange bears some resemblance to good conversation - it is strictly a reciprocal affair. Is is almost impossible, out-of-doors, to vary the flow from one source without at the same time varying that from another. As an example, stepping out of the sun to the shade of a tree changes the amount of sunlight falling on the body, but that is not the whole of it. It also affects the radiant exchange between body and ground, and the extent of the reradiation of the body to space. Possibly other factors are also affected. The terms of the radiation exchange equation are evidently interdependent - a change in one may cause change in many or all of the others.

This is one of three threads which run as a theme through this discussion. The second thread concerns the necessity of including radiation gains and losses in calculations of heat loss out-of-doors. Evaporation notes have sometimes been taken as the sole measure of heat transfer under these conditions. The third thread, a corollary of the first two, considers the changes in radiation exchange as surface temperatures change. This may well act as a compensatory device to form a kind of insulating layer which decreases the effective radiation load. These may appear to be elementary propositions, radiation exchange, however, although complex in practice, is relatively simple in theory.

As Dr. Plummer stated, this complexity of factors, this handling of the numerous variables, poses a nice problem in maneuvers. It is literally true that almost everything under the sun affects radiant transfer out-of-doors. Most of the factors affecting climate- the position of the body; nature of the terrain; materials of the clothing- these include some of the most important.

There are five sources of radiant heat exchange between the body and its environment - (1) solar radiation, (2) diffuse radiation from the sky, and (3) and (4) two types of radiation from the ground. Reradiation from sun and sky is diffusely reflected from the ground at unchanged wavelengths. In addition, the ground will radiate according to the fourth power of its absolute temperature. At these long wavelengths, both ground and body may be considered as black bodies - that is, emissivity and absorptivity equal to unity. Out-of-doors, the radiation of the body to cold space (5) must be included in the calculations. The radiant exchange may therefore be expressed as-

$$Z = Z_o + Z_h + Z_g + Z_1 - Z_s$$

Where Z = Net radiant exchange - total radiant heat stress on body

Z_o = Direct solar radiation

Z_h = Diffuse sky radiation

Z_1 = Reflected radiation

Z_g = Ground radiation

Z_s = Radiation from the body to the sky reduced by incoming radiation from the atmosphere

We begin with the solar constant, which is the amount of solar energy which falls per minute on one square centimeter outside the atmosphere. The general accepted figures is 1.94 Cals/M^2/min. This is depleted and modified somewhat as it passes through the atmosphere. Scattering will be caused by gaseous molecules, water vapor, and dust. Absorption will occur due to ozone, Co_2, water vapor, etc. The effective length of path through the atmosphere varies with the secant of the zenith angle of the sun, being twice as great when the sun is 60° from the zenith as when the sun is overhead.

Scattering of solar radiation by air and water vapor, and absorption by water vapor, for various angles of the sun, as determined by latitude, season, and time of day, are taken directly from the data of the Smithsonian Institution. (Smithsonian Physical Tables, Table 686, page 555, 8th revised edition). Ozone absorption cuts off transmission of the solar specturm at 2.9, but the loss in intensity is small in this range of the spectral intensity curve.

Water vapor is the principal absorber of radiation in the infra red. The effect is so marked that solar radiation received at normal incidence is on the average higher in the winter when the air is dry than the summer. The highest solar radiation ever recorded in Washington occurred on a February day when the temperature dropped suddenly to the lowest point in twenty years.

Particles of dust, being large, are generally considered to scatter light independently of wave length. As dust content of

the air is difficult to estimate, it has been disregarded in the calculations. This seems to be a reasonable procedure, as we are most interested in maximum stress. Actually, our calculations run five or six percent higher than recorded measurements of solar radiation at Washington. Independent measurements here estimate that "average" dust content lowers solar radiation by about 6%.

Measurements of the albedo of human skin indicated that blonde skin reflects 43% of solar radiation, brunette skin somewhat less, and negro skin about 16%. As measurements on military cloths by Dr. Aldrich for Dr. Wulsin give figures of 40% to 50%, the transmission is included in the absorption figures, since it is small, from 0 to 5%, and is absorbed close to the surface. (This recalls the fact that radiation cannot always be considered as entirely a function of the surface. The most apague material becomes translucent if thin enough, and the most transparent material becomes apague with sufficient thickness.) An average between absorption of blonde skin and herringbone twill has been used here.

Now for the geometry involved in determining the amount of direct solar radiation falling on the human body. For a person standing up, it will be least when the sun is overhead and will increase as the sun descends in the sky. On the other hand, the stress on the prone body will be greatest for an overhead sun, and will decrease as the sun descends. We have used profiles of body area measured by Dr. Harold F. Blum, to whom I am indebted for his valuable cooperation.

An average figure for diffuse sky radiation is 15% of direct solar radiation, the range in Washington, on the average, running from 10% in winter to 20% in summer. We have taken three percentages as representative, 5% for very dry air, 15% for average air, and 20% for moist air. A consideration of the geometry shows that, in this case, the amount of radiation received is independent of the position of the body. When lying down, one-half of the body received radiation from half the sky (considering the body as a flat-two-sided affair). If the body is considered to be a many sided prism, or, if you will a cylinder, the same relationship holds.

Since the reflection of radiation by the terrain depends on the albedo of the surface, it is unfortunate that most albedos have been measured photometrically. A reflectivity of 25% for desert sand, measured over the entire spectral range, is employed as the basis of our calculations, once again a maximum figure. If the ground is flat, the erect body will receive approximately half the radiation emitted by unit area. This may be demonstrated mathematically, it being sufficient to note at this time that the sides of the body are exposed to half the solid angle through which radiation passes.

(Discussion of the chart of total solar radiation falling on the human body followed. It was suggested that 130 Kg.Cals/ M^2/hr. be taken as an average value for the total solar load in clear weather. It was pointed out that for position of the sun not far from the zenith (an average summer noon position) the

variation with varying moisture content of the air is small. It must be remembered that this is a maximum, based on clear weather, dust free air, high reflectivity of ground surface, and low reflectivity of clothing or skin surface.)

Direct radiation from the ground may be treated in the same manner as the radiation diffusely reflected by the earth's surface, the one divergence from this procedure being due to the fact that both emitter and receiver are now treated as black bodies. The ground temperature which determines the intensity of radiation may theoretically reach 200°F, although the recorded upper limit is 180. Desert sands reach 140 to 180, and even dry grass normally attains a temperature of 110° to 125°F in the sun, with occasional readings of 150°F, with green grass running about 20° cooler, according to Dr. Brooks. Moisture content of the ground surface certainly affects the temperature - indeed, the high temperature of rocks in the sunshine may be attributed to their dryness.

Water vapor, a powerful absorber of infra red radiation, is even more effective in this region of very long wave lengths. (Chart indicates how much is completely absorbed). As a matter of fact, its action cannot be ignored even in the small amounts which occur in the radiation path between the body and its surroundings. The average amount of moisture in the air may account for a reduction of as much as 10%. Indoors as well as out, the absolute amount of water vapor present must be considered.

Unquestionably, the most difficult radiation flow to handle practically is that of the body to cold outer space. The outward

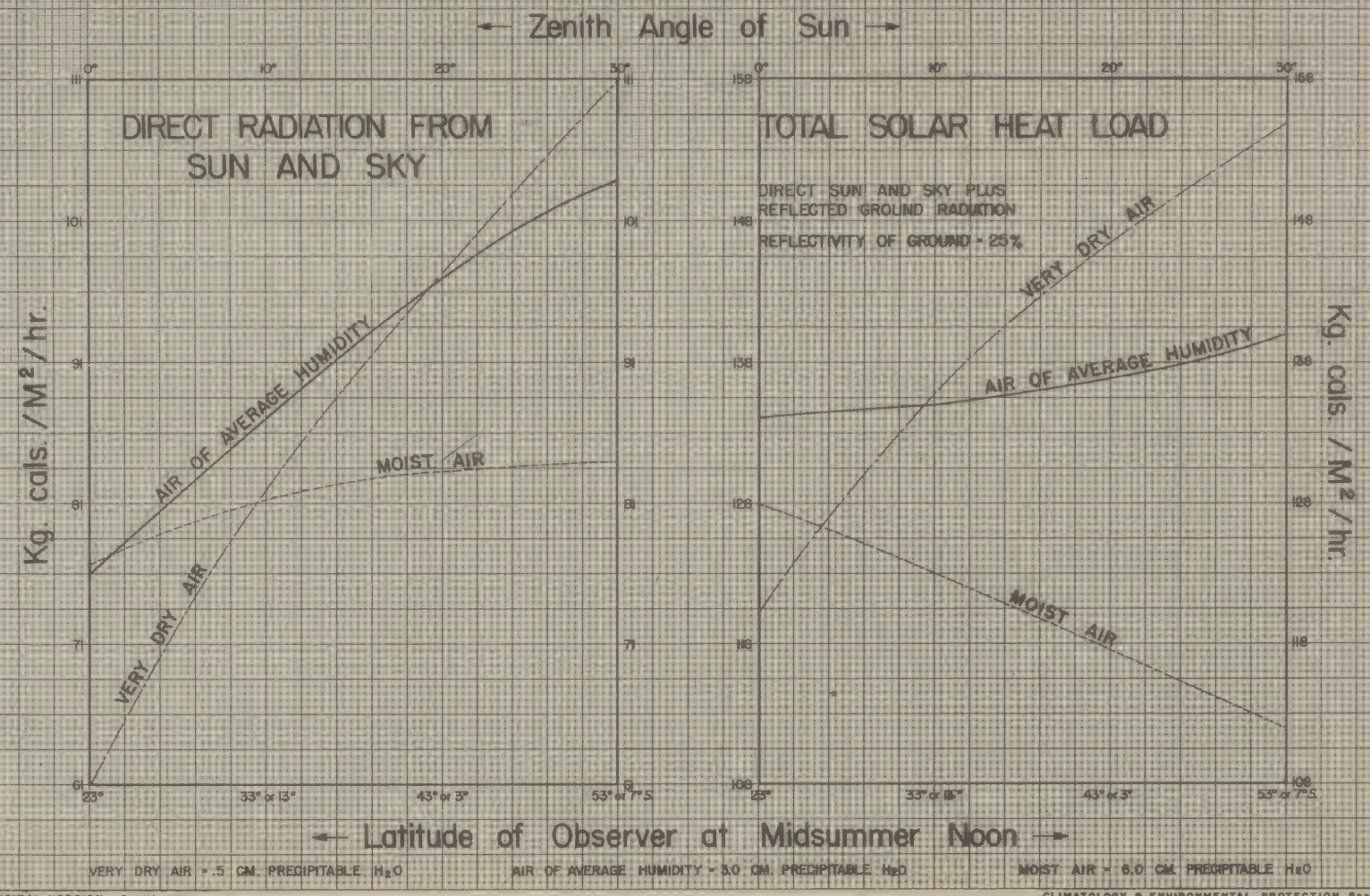
radiation of the body amounts to 216 Kg.Cals/M^2/hr., the net radiation exchange of the body being this figure reduced not only by incoming radiation from the sources already discussed, but also by radiation from that highly variable unknown quantity, the atmosphere. Although the radiation to space of the body itself has not been studied, the nocturnal radiation of the atmosphere has received a great deal of attention. Extrapolation of results made on instruments at air temperature yield a tentative figure of 90 Kg.Cals/M^2/hr. lost from the body to the sky, clear weather, vapor pressure about 13 (fairly average humidity conditions) skin temperature 96°F. This is quite independent of all radiation at shorter wave lengths, coming in from the sun, either direct or diffused as sky radiation. Indoors, where walls and ceiling temperatures, approximate body temperatures, the radiant exchange is small. Merely stepping out-of-doors on a clear night, when there is no incoming solar radiation to balance it, causes a sharp increase in heat loss; this after a time becoming minimized by the reduction in surface temperature of skin or clothing. Increase in temperature and moisture content of the air decreases the net loss from the body, to a point where the exchange is almost zero in heavy clouds.

Radiation is a surface phenomen, and as has been previously mentioned, any change in incoming radiation tends to change surface temperatures, thereby causing further adjustment in the exchange. This mechanism may, on occasion, operate to minimize the radiant heat load on the body.

Little is known of the temperature of clothing surfaces. The Smithsonian Institution is making preliminary measurements at the present time. When there are completed, they may be applied to the study of heat transfer through clothing to the skin, and a more complete picture obtained for sunshine conditions.

FIGURE 13

RADIATION DUE TO SUNSHINE FALLING ON THE ERECT HUMAN BODY



ORIGINAL VERSION - 8 AUGUST 1944

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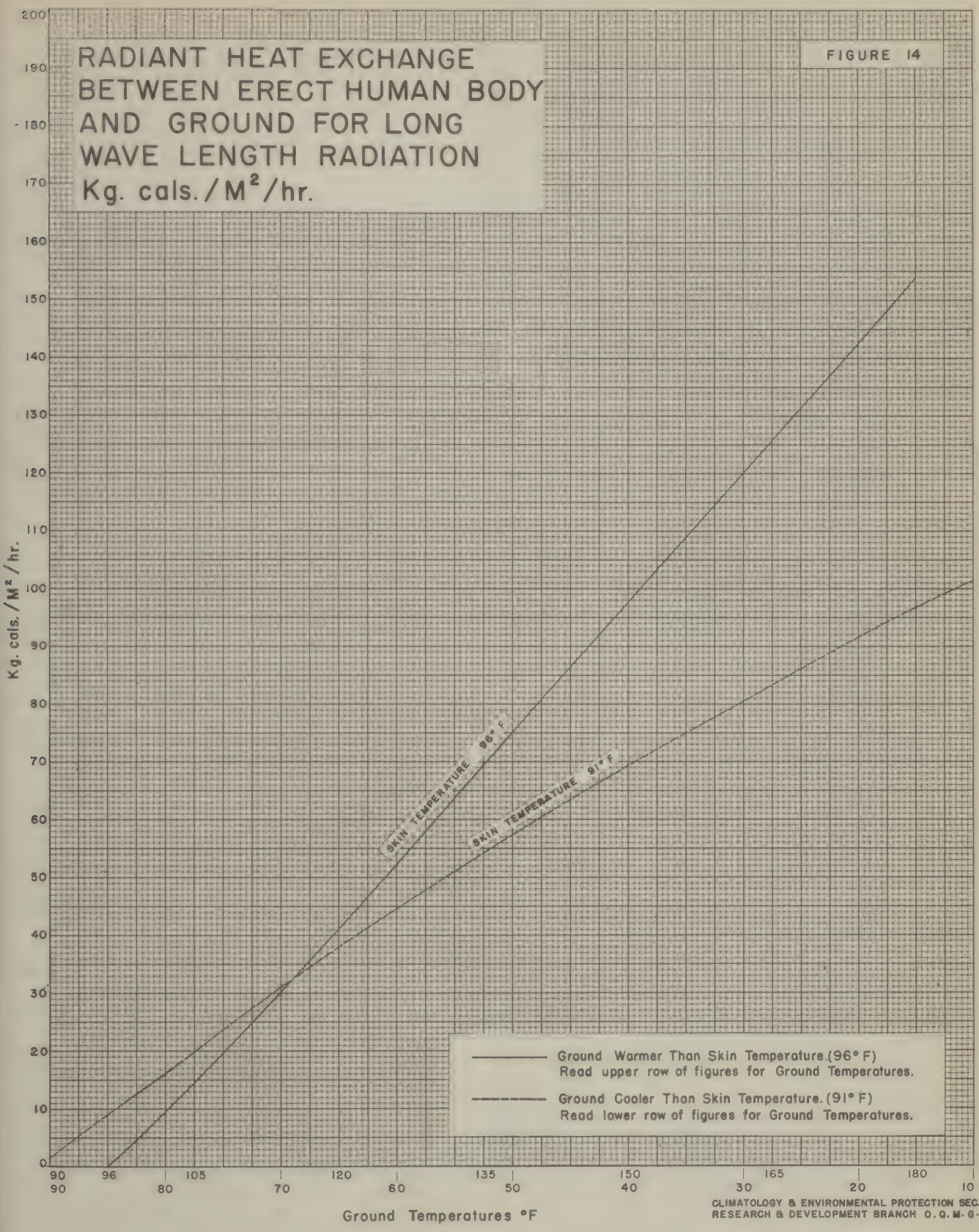
RADIANT HEAT EXCHANGE BETWEEN ERECT HUMAN BODY AND GROUND FOR LONG WAVE LENGTH RADIATION
Kg. cals./M²/hr.
FIGURE 14
Kg. cals./M²/hr.
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
SKIN TEMPERATURE 96° F
SKIN TEMPERATURE 91° F
Ground Warmer Than Skin Temperature.(96° F)
Read upper row of figures for Ground Temperatures.
Ground Cooler Than Skin Temperature. (91° F)
Read lower row of figures for Ground Temperatures.
90 96 105 120 135 150 165 180
90 80 70 60 50 40 30 20 10
Ground Temperatures °F
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25-10935-200

DISCUSSION

DR. HAROLD F. BLUM:- It seems to me that what we need is a lot of measurements we do not have. Unless we could go on to the desert and make measurements simultaneously of all these factors, we can not hope to get a balance sheet or to say very much about what the actual load is.

For purely illustrative purposes, a thermodynamic balance sheet is presented for a hypothetical set of conditions, namely; sun at zenith, temperature of the terrain 60°C, ambient air relatively dry and at a temperature somewhat above that of the body, the man erect marching at 3 miles per hour. The evaporation factor is based on the loss of 882 gms. of water per hour, an average figure obtained by Adolph for men walking on the desert. Convection and conduction losses are assumed to be small because the temperature of the ambient air is near that of the body, but represent an unknown value. The radiation values are those calculated in this paper.

	Kilogram Calories Per Hour
Metabolism	+265
Total solar heat load	+234
Long wavelength radiation exchange with terrain	+128
Long wavelength radiation exchange with heavens	-128
Evaporation	-506
Convection and conduction	± ?
Total	-7 ±?

The close over all balance obtained is fortuitous, as is the exact balance between radiation from the terrain and to the heavens. Had the

ground temperature been taken as 10° lower or the assumption made that the sun had warmed the clothing to a temperature 10° higher than that chosen, the balance would be considerably upset. It should be pointed out that for a man at rest, the long wavelength radiation exchange would be more important relative to the metabolism, and it might be interesting to explore other possibilities.

The evaporation factor must adjust itself to achieve a balance if the body temperature is not to rise. Hence it must be expected to vary as the other factors shift with the conditions, and when the magnitude and variability of the other factors are considered, it does not seem surprising that Adolph and his coworkers should have obtained different values for evaporative heat loss under the various conditions they explored, nor that these values display the general consistency they do.

The whole problem of radiant exchange with outdoor surroundings is, thus, quite complex and cannot be accurately simulated in an enclosed room. Moreover, all these factors render physiological measurements out of doors subject to considerable variability, not only insofar as the solar heat load is concerned, but with regard to the heat load as a whole.

SUMMARY

DR. PLUMMER:- In the previous discussion we have covered as thoroughly as possible all of the avenues of heat loss normally available to the human body. Equilibrium can only occur if the heat production is equal to the heat loss, and this may be used to provide an index or indices which may be used to evaluate climatic stress. For cold

weather conditions we may use as an index the insulation requirements to provide equilibrium when the activity, temperatures, wind velocities, etc., are known. Any scale of activity may be chosen, but two specific ones appear to be the most desirable. For normal daylight conditions, 75 Kilogram Calories has been chosen because men in the Army spend a considerable portion of their time working at this level. An index set up on this basis, however, would not be adequate for night conditions as the metabolic rate of the sleeping men is very much lower.* Consequently, it seems that two indices are necessary, and on the basis of previous discussions the insulating value of the clothing required to maintain equilibrium may be calculated. An example for day is shown on the map of Central Europe, which shows the clothing required for winter daylight conditions for various parts of the country.

The situation is very much more complex, however, in the tropical or high temperature conditions, as it is not possible to control heat loss by the mere removal or addition of extra clothing. In many of these places a certain amount of clothing must be worn as a protection against other factors of the environment, such as mosquitoes, jungle vegetation, etc. As the clothing requirements are fixed by other conditions and the environmental conditions are also fixed by the locality, the only variable which remains is the rate of activity. We have chosen as an index of climatic stress the maximum activity which may be permitted in a given environment without causing an increase in the stored heat within the body. This work is not a comfort index, but represents the maximum conditions in which men may be expected to work indefinitely. An index based upon comfort and

*For mapping according to the index see Appendix II.


4
6
8
10
12
14
16
18
20
22
54
52
50
48
PRUSSIA
STETTIN
GERMANY
AMSTERDAM
BERLIN
WARSAW
POLAND
PRAGUE
MUNICH
CZECHOSLOVAKIA
AUSTRIA
AVERAGE CLOTHING REQUIREMENTS FOR JANUARY
Based on the Mean Monthly Temperature; Wind Velocity of 5 M.P.H., and in Dry Shade. Calculated to Maintain Continuous Comfortable Protection for Men Standing Around (75 Kg. Cals./M²/Hr.
Insulation Clo Values
Effective Insulation Thickness (inches)
Limiting Temperature °F.
2.00 to 2.50 0.50 to 0.63 46 to 37
2.50 to 3.00 0.63 to 0.75 37 to 28
3.00 to 3.50 0.75 to 0.88 28 to 19
3.50 to 4.00 0.88 to 1.00 19 to 10
4.00 to 5.00 1.00 to 1.25 10 to -7
5.00 to 6.00 1.25 to 1.50 -7 to -23

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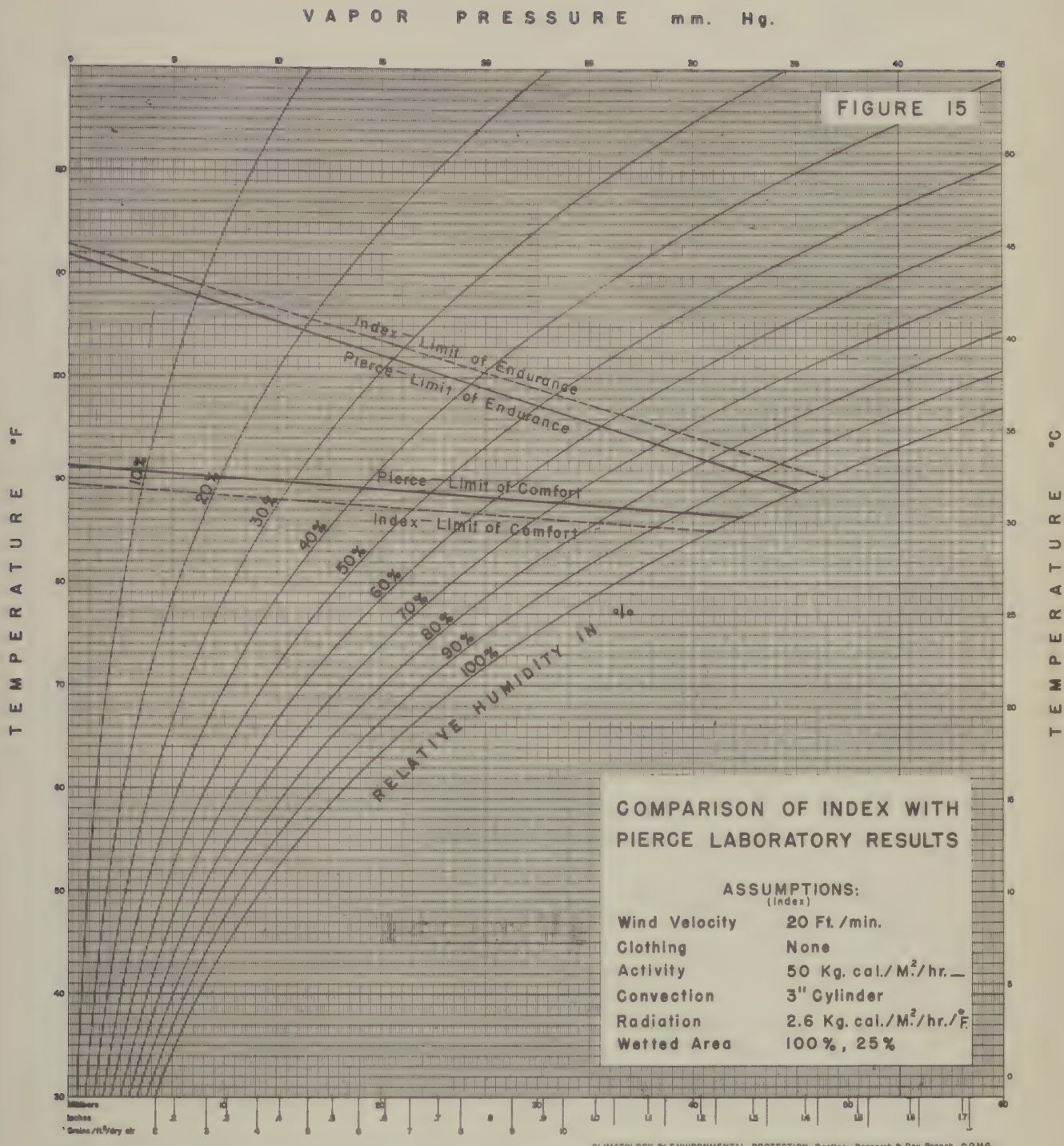
inefficient discomfort could also be calculated by using a wetted area of the body surface of 25%, and 75% respectively.

In calculations of maximum activity, we have been forced to eliminate the effect of radiation. Data is available for so few parts of the world that we can only calculate an index on a basis of convection, conduction, and evaporation. The calculations of radiation can be used to estimate the possible effect of the radiant heat load. The index as we use it excludes radiation, but in all cases it must be borne in mind that radiation may add a very definite heat load and its effects must be considered in those localities in which the maximum permissible activity begins to approach normal activities.

As a comparison of the results achived with an index of this type, we have compared our index of various activities with the work of the Pierce Laboratory, the A.S.H.V.E. Laboratory, and Dr. Robinson's recent work.

The comparison of the index with Pierce Laboratory results is shown in Figure 15. It is interesting to note that the limit of endurance calculated by the index (equilibrium conditions) lies in regions of slightly more severe conditions than those indicated by the Pierce Laboratory. In terms of temperature differences, however, the index is within 1° of the Pierce Laboratory figures for all vapor pressures. For the limit of comfort, the index is within $1\frac{1}{2}^{\circ}$ of the Pierce Laboratory results for all vapor pressures.

In making this comparison, certain assumptions have been necessary, and all of the assumptions used in calculating the index


VAPOR PRESSURE mm. Hg.
FIGURE 15
TEMPERATURE °F
TEMPERATURE °C
Index - Limit of Endurance
Pierce - Limit of Endurance
Pierce - Limit of Comfort
Index - Limit of Comfort
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
RELATIVE HUMIDITY IN %
COMPARISON OF INDEX WITH PIERCE LABORATORY RESULTS
ASSUMPTIONS: (Index)
Wind Velocity 20 Ft./min.
Clothing None
Activity 50 Kg. cal./M.²/hr.
Convection 3" Cylinder
Radiation 2.6 Kg. cal./M.²/hr./°F.
Wetted Area 100%, 25%
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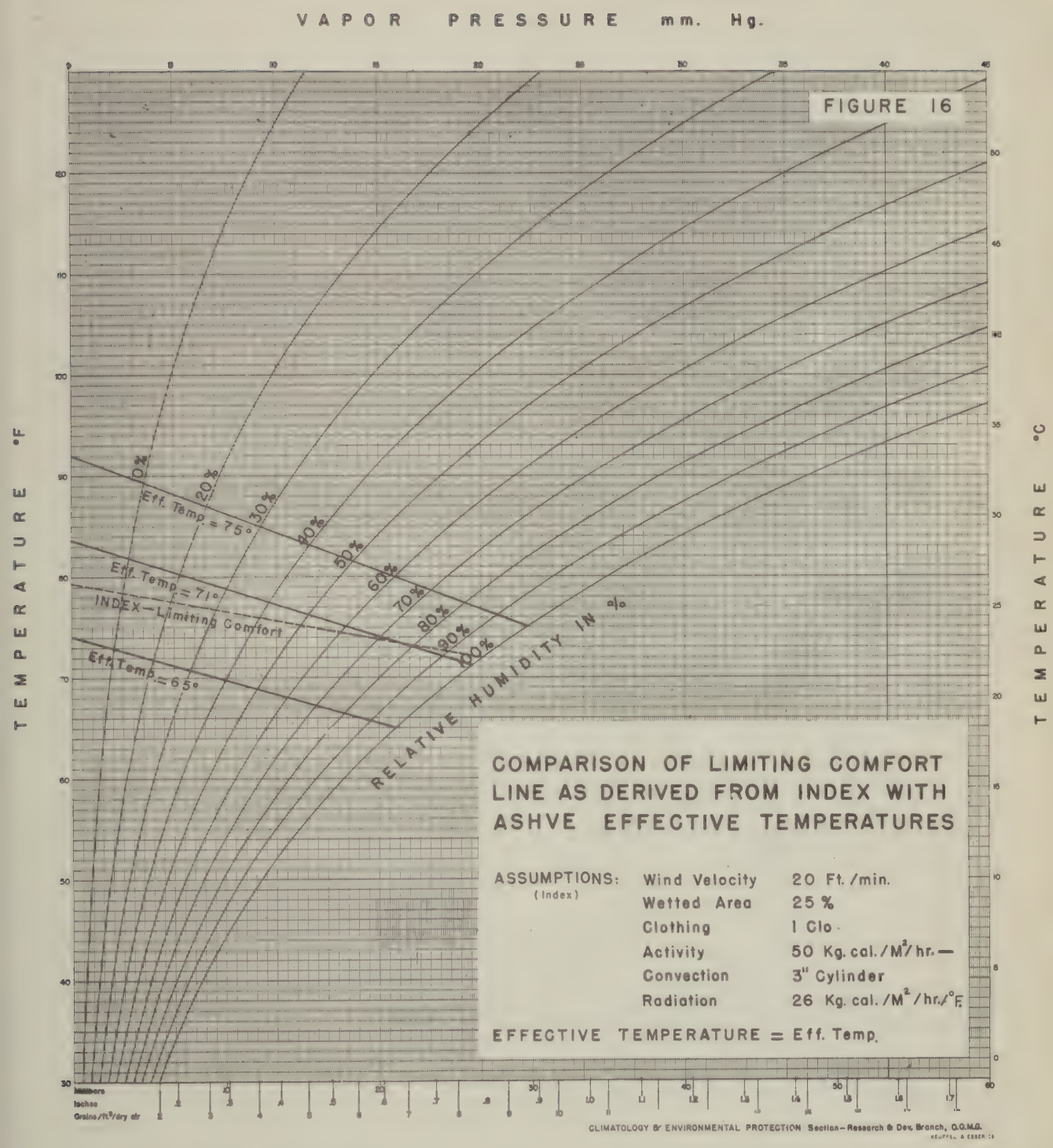
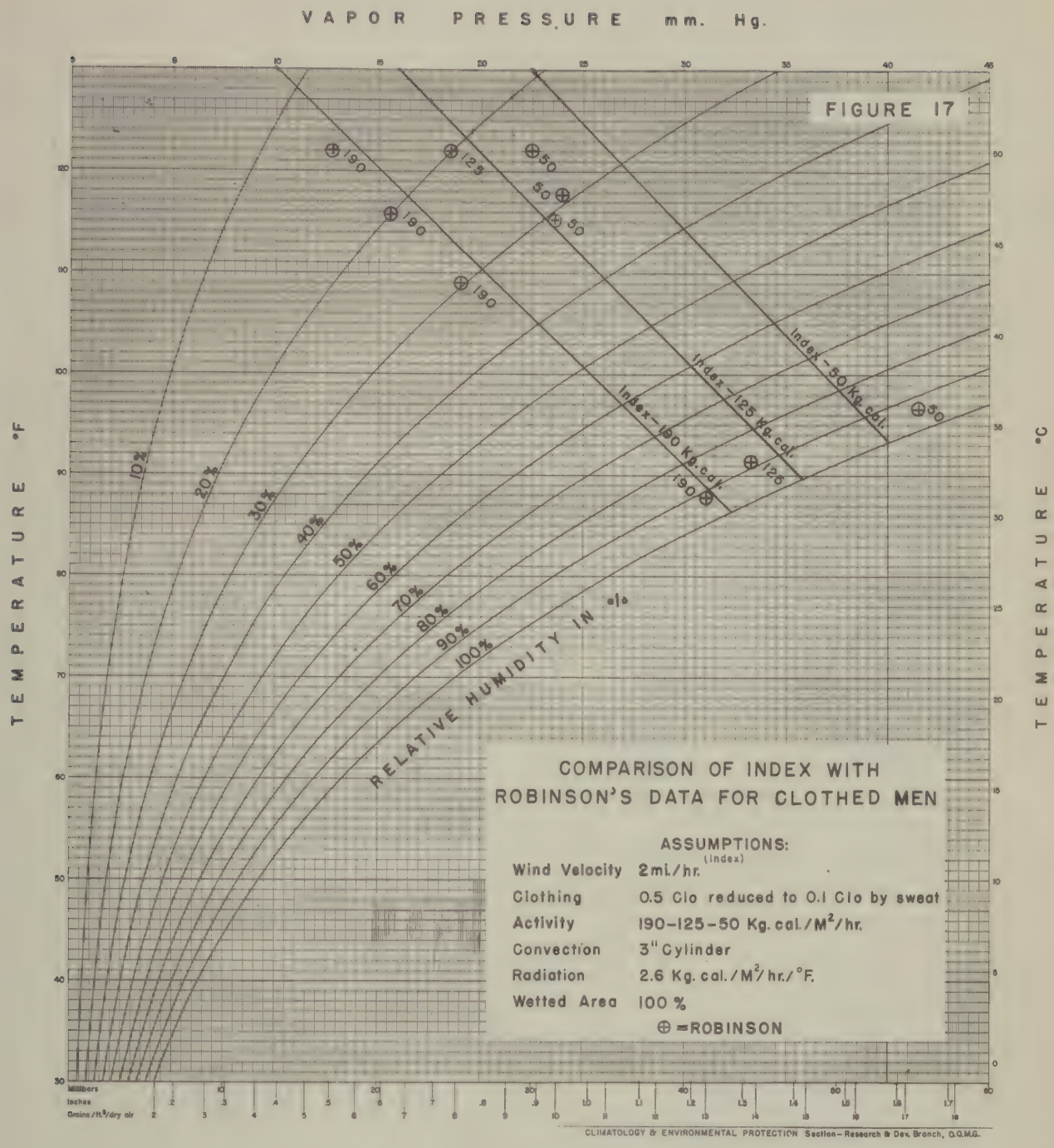
are listed in Figure 15. A slight change in wind velocity would affect the slope of the lines, and also a small change in the percent of wetted area would appreciably affect the position of the lines. However, the agreements seem remarkably good.

Figure 16 shows a comparison of the limiting comfort line as derived from the index with the ASHVE effective temperatures. Again, because of lack of data, it has been necessary to make certain assumptions, and these assumptions are listed on the chart. It will be seen that the limiting comfort line becomes very close to an effective temperature of 71° line by a change in the wind velocity figures. Considering the absence of exact data and also that the ASHVE experiments demarcate a zone of comfortable sensation through which a line has been drawn according to a probability curve, this figure likewise shows good agreement between the index and experimental figures.

In figure 17 we have shown a comparision of the index with the experimental work of Dr. Sid Robinson recently published in Report No. 12. Here the index lines represent the limiting conditions of temperature and vapor pressure for different activities at wind velocity figures used in Dr. Robinson's experiments. It will be seen that the agreement for activity of 190 Kilogram Calories and 125 Kilogram Calories is excellent, although the agreement is not quite so good as for activities of 50 Kilogram Calories.

Figure 18 shows a comparison made in the same way of the index with Dr. Robinson's experiments on nude men. Here the qualitative agreement is quite good, but the quantitative agreement leaves something to be desired. Unfortunately, at the present time we are not able to


VAPOR PRESSURE mm. Hg.
FIGURE 16
TEMPERATURE °F
TEMPERATURE °C
Eff. Temp. = 75°
Eff. Temp. = 71°
INDEX—Limiting Comfort
Eff. Temp. = 65°
0%
20%
30%
40%
50%
60%
70%
80%
90%
100%
RELATIVE HUMIDITY IN %
COMPARISON OF LIMITING COMFORT LINE AS DERIVED FROM INDEX WITH ASHVE EFFECTIVE TEMPERATURES
ASSUMPTIONS: (Index)
Wind Velocity 20 Ft./min.
Wetted Area 25 %
Clothing 1 Clo
Activity 50 Kg. cal./M²/hr.
Convection 3" Cylinder
Radiation 26 Kg. cal./M²/hr./°F.
EFFECTIVE TEMPERATURE = Eff. Temp.
Millibars
Inches
Grains/ft.³/dry air
CLIMATOLOGY & ENVIRONMENTAL PROTECTION Section—Research & Dev. Branch, O.O.M.G.


VAPOR PRESSURE mm. Hg.
FIGURE 17
TEMPERATURE °F
TEMPERATURE °C
RELATIVE HUMIDITY IN %
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Index - 190 Kg. cal.
Index - 125 Kg. cal.
Index - 50 Kg. cal.
190
125
50
Millibars
Inches
Grains/ft³/dry air
COMPARISON OF INDEX WITH
ROBINSON'S DATA FOR CLOTHED MEN
ASSUMPTIONS:
Wind Velocity 2 mi./hr. (index)
Clothing 0.5 Clo reduced to 0.1 Clo by sweat
Activity 190-125-50 Kg. cal./M²/hr.
Convection 3" Cylinder
Radiation 2.6 Kg. cal./M²/hr./°F.
Wetted Area 100 %
⊕ = ROBINSON
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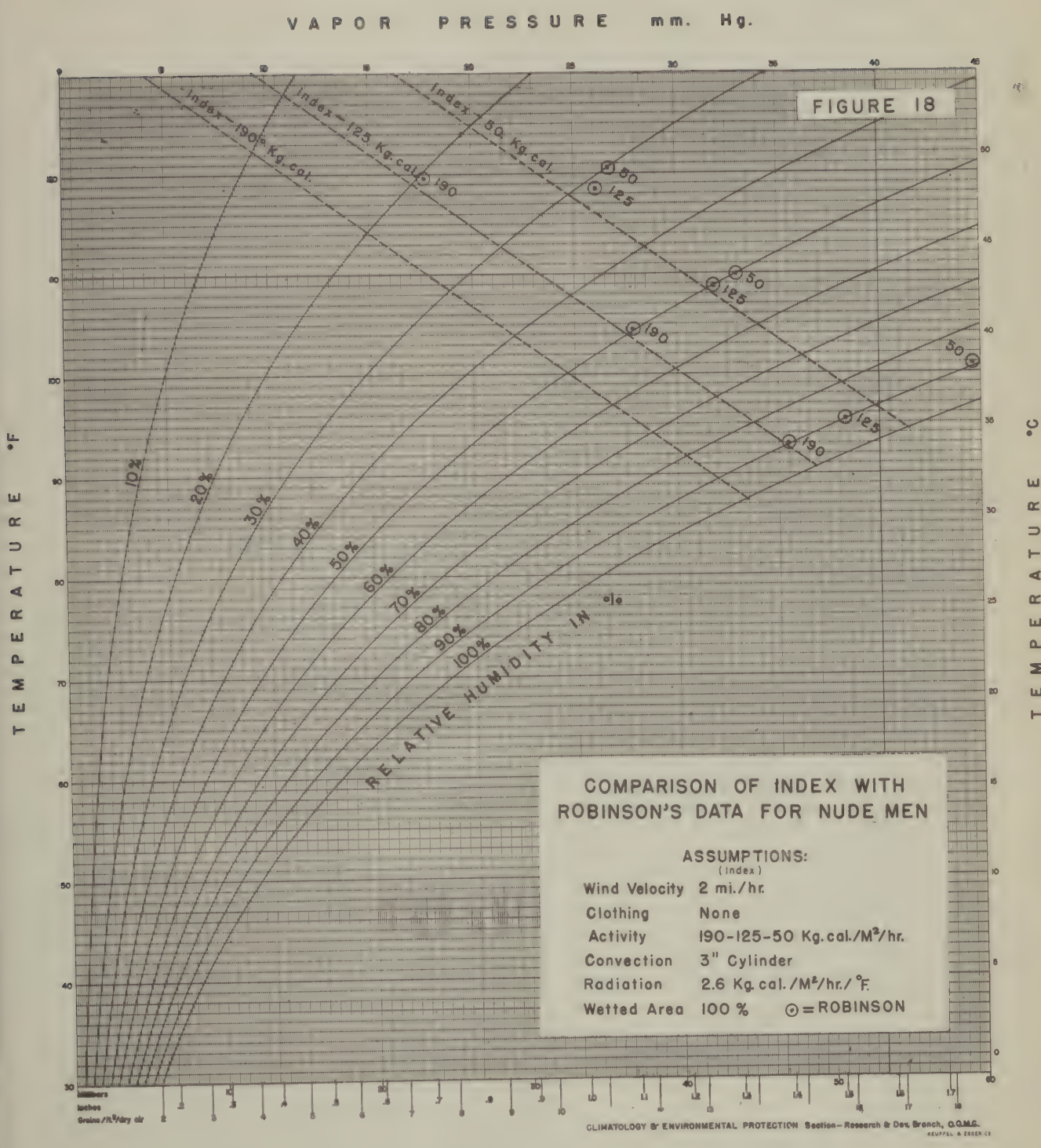
VAPOR PRESSURE mm. Hg.
FIGURE 18
TEMPERATURE °F
TEMPERATURE °C
Index 190 Kg. cal.
Index 125 Kg. cal.
Index 50 Kg. cal.
190
125
50
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
RELATIVE HUMIDITY IN %
COMPARISON OF INDEX WITH ROBINSON'S DATA FOR NUDE MEN
ASSUMPTIONS:
(Index)
Wind Velocity 2 mi./hr.
Clothing None
Activity 190-125-50 Kg.cal./M²/hr.
Convection 3" Cylinder
Radiation 2.6 Kg.cal./M²/hr./°F.
Wetted Area 100 % ⊙ = ROBINSON
Millibars
Inches
Grains/ft³/dry air
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explain the difference.*1

The proposed formula for mapping the index is as follows:

I. Cold Weather Index:-

A. Equilibrium index for standing men*2

$$1 \text{ clo} = \frac{3.09\ (T_s - T_a)}{M - S - (E + A)} - I_a$$

in which M is 75 Kg.Cals/M^2/hr,
and S is 0

B. Index for 8 hours comfortable sleep

Equation as above, except that -

M = 40 KgCals/M^2/hr, and
S = 5 KgCals/M^2/hr

II. Hot Weather Index:-

Maximum Metabolism - Evaporative Heat Loss ± Convective Heat Transfer, ± Radiation

in which Radiation is generally omitted, but its possibilities should never be excluded.

DISCUSSION

COLONEL HATCH:- As far as the index is concerned, from the present discussion, I gather that this is based purely on equilibrium conditions. At Fort Knox our experiments have been based instead upon the ability of a man to perform a definite amount of work for a four-hour period. How would you expect these results to tie in with an equilibrium index?

*1 A tentative explanation of this difference will be furnished in a future paper

*2 For explanation of symbols see Appendix 2 together with further details of correlation with other experiments.

DR. PLUMMER:- In developing such an index, it is almost axiomatic to first attempt to solve the problem for equilibrium conditions and then modify the solution for short period conditions. From the purely theoretical side, I would think that we would be able to relate the equilibrium index to an index for four-hour periods, or any other perids, if we knew definitely the quantity of heat storage that could be permitted. We would also have to know what skin temperatures and rates of sweating would be possible during this period of time as a change of 1 or 2 degrees in skin temperature increases the possible evaporative cooling quite appreciably. We would be very glad to have any data on either time, period, or equilibrium tests as, unfortunately, there is very little available with which we may check our results.

DR. BURTON:- I feel that at present the calculation of the tropical "Index" is far from reliable. The excellent work of Dr. Plummer and Mrs. Schickele has given us the value of the heat absorbed from solar radiation in KgCals/M^2/hr, but how should this be included in the index? There is an "efficiency factor" by which it must be mulitiplied before it is added to the metabolic heat, since the insulation of clothing protects a man from receiving all the heat that is absorbed on the surfaces of the clothing. Also, the very important drop in physiological efficiency of evaporation when evaporation takes place from the surface of clothing instead of directly from the skin is not included. A further difficulty is that for the values of prevailing wind velocity, which so greatly affect the calculation of the index, one could take only the values supplied by the meteorologist. These are usually taken on top of a tall pole and might have little relation to those affecting

a man in the jungle.*

DR. PLUMMER:- I don't agree that the calculation of the tropical index is far from reliable. For mapping purposes, we calculate the index on a basis of convective and evaporative heat transfer at relatively low wind velocities, generally of the order of two to three miles per hour. This wind velocity is so low that an active man may readily produce it through his own motions, whereas the resting or sitting individual will have, naturally, a much lower metabolic rate and consequently not require as high a loss. Furthermore, the purpose of the index is not necessarily to indicate the relative ease of performing work, but is primarily expected to point out the danger areas of the world where maximum protection is required. Also, we expect, through a quantitative study of heat losses, to obtain a more accurate understanding of the type of protection required. We are only too ready to admit that a great deal remains to be done, but we do feel that an index as derived from the present work is at least a good first approximation. As more data becomes available, we will be glad to modify or correct the results.

At present we are unable to incorporate radiation in the index, primarily because of the lack of data and also because of the variability of conditions. We feel that the tropical index should be used primarily on a basis of convection plus evaporation, but <u>bearing in mind that the radiant heat load may add a definite quantity</u>. We have attempted to evaluate this load and calculate the probable limits.

*A theoretical analysis of the efficiencies referred to and their consequences is now being written by Dr. Burton.

APPENDIX I

The original purpose of the meeting was to present the basic laws of heat transfer as applied to the human body by physicists and physiologists to a group of meteorologists, climatologists, and geographers. Unfortunately, the meeting fell behind schedule in the late afternoon and too little time remained to give the climatologists an opportunity to make preliminary comments on the formula or on the problem of the application of these physical laws to climatic data for mapping purposes. Also the transcript of this part of the meeting was too insufficiently kept to permit complete reconstruction. Major Heald presented some of the basic problems, followed by various overall random comments by various meteorologists, climatologists, and geographers present.

Just as it was frequently necessary in the establishment of the index to set forth assumptions, it will be necessary for the climatologists to assume certain average values of climatic elements before they will be able to apply the index to mapping techniques. Temperature is constantly in fluctuation, as well as wind, humidity, and solar radiation. Each climatic element introduces a problem, because average values cannot give a complete picture. In the tropics the human being is most concerned with the maximum heat, the radiation, humidity, and low wind speed. In the cold regions, the body is under greatest stress when the temperatures are lowest and the wind is strongest.

Mean or average monthly weather conditions fail to reflect the average worst condition. To show only the average worst conditions

would give a distorted impression for it can only express the actual stress that would occur for a brief period. It is probable that plotting of stresses will require the use of average values with some method used to show the average daily range.

Considerable experimentation will be necessary before a suitable technique can be developed for mapping. The climatologists in the Office of the Quartermaster General are now beginning this work, and it is hoped that others will also apply their thoughts to the application of the index. It is expected that the meteorologists, climatologists, and geographers present at the meeting, as well as others concerned, will meet later to consider in detail the application of the index to mapping techniques.

Anticipating many of the problems which will arise in mapping the index of climatic stress, the climatologists of the Climatology and Environmental Protection Section have summarized some of the troublesome factors that may appear:

TEMPERATURE

Whether mean maximum, average, or mean minimum temperature data should be utilized.

Whether any employment should be made of the frequency ranges of temperatures.

EVAPORATION

The deficiencies of relative humidity data as it is published.

Difficulties of determining vapor pressures from available data.

Whether the minimum or maximum vapor pressure should be used.

What consideration must be given to variations of vapor pressure.

WIND VELOCITY

A means of extending the scattered material that is available.

Whether the mean wind speed has any significance.

Reduction of wind speed from anemometer level, and associated assumptions as to Austausch and its variations.

RADIATION

Rapid calculation of the zenith angle of the sun, considering diurnal, annual, and latitudinal variation.

Extending the sparse radiation measurements that have been made, and utilizing them.

Substitution of data on duration of bright sunshine for radiation values.

Substitution of data on mean cloudiness for radiation data.

Difficulties of using data on either sunshine duration or mean cloudiness.

Assumptions of the temperature of the ground and vegetation.

GENERAL

The major problem involved in employment of the mean to represent climatic elements that have large diurnal, seasonal, and aperiodic variations.

The increase of this problem in geometric progression when single climatic elements are brought together in indices of two, three, or four components.

The group of problems involved in converting observational data from the location where instruments are exposed to the environment of the soldier.

The general difficulties resulting from lack of observations of certain elements over large areas.

APPENDIX II

Basic Information Necessary for Determining Clo Values

1. The metabolic clo equation as originally developed by Drs. Gagge, Burton, and Bazett is as follows:

Clo Value Required for Complete Comfort =

$$\frac{3.09\ (T_s - T_a)}{M - S - (E + A)} - I_a$$

Where M = Metabolic heat in KgCals/M^2/hr

S = Bodily Heat Debt

E = Total heat lost by evaporation from body and lungs

A = Heat lost by warming the inspired air

T_s = Temperature of the skin in ^oF

T_a = Temperature of the ambient air in ^oF

I_a = Resistance of the still air in clo units

2. Metabolism as a Function of Activity:- The heat created by the body under various activities is generally accepted as follows:

Activity	Metabolism in Kg.Cals/M^2/hr
Sleeping	40
Sitting still	50
Truck driving or standing still	75
Slow walking	100
Marching at 3 miles an hour	150
Marching at 4 miles an hour	200
Heavy activity such as mountain climbing or ditch digging	300-600

3. Time and Clo Values:- The original formula as given above only posits the Clo Value necessary to keep a man in equilibrium so that he is losing the same amount of heat as his body creates. It often happens, however, that a man may be inadequately clothed for the temperature at which he finds himself, even though his clothing is well-balanced over

all portions of his body. His endurance of cold will then be limited by a time factor, which is technically known as the tolerance time.

Obviously it is not always necessary to provide clothing which will keep a man comfortable indefinitely. If he is to stand guard duty for four hours only and is certain of a warm room in which to regain his lost heat afterwards, he need have far less protection than a man who is going to drive a truck for eight hours at the same temperature. For mapping purposes, we have assumed that indefinite protection is necessary at a low activity, such as truck driving, if the temperatures chosen are the monthly average of the daily mean. It is not necessary, however, to map indefinite protection for sleeping bags. Eight hours at average minimum temperatures is quite sufficient.

Graphs illustrating tolerance times as a function of activity, clo value, temperature, and wind velocity are given. These are based on the equation - Time x Intensity equals a Constant. The original formula was applied to unbalanced conditions, where the footgear was inadequate compared to the other garments. The plottings made were checked with data on tolerance time received both from the Climatic Research Laboratory and from the Harvard Fatigue Laboratory. Tolerance time under such conditions follows the locus of a point on various cooling curves where the average skin temperature of the foot falls a certain specified number of °F (for example from 89°F to 55°F).

This formula was extrapolated to make it more usable for general metabolic heat loss rather than for local cooling time curves as follows:

$$\text{Time} - \frac{\text{Heat Loss x Resistance}}{\text{K Temperature Difference}}$$

The following assumptions have been made:

a. That the clothing is equally adequate all over the body, i.e. that there are no local cooling points.

b. The total heat debt of 80 Kg.Cals/M^2 was taken as the limit of endurable cold. This is thought to be a conservative estimate since much greater losses have been recorded at various laboratories. However, because no clothing is completely balanced and because susceptible subjects need to be protected, it was thought best to assume a conservative loss. The value of 40 Kg.Cals. was taken as the total loss which a man might endure while still remaining asleep. This is based on a statement made in the Harvard Fatigue Laboratory Report No. 19 and is corroborated by the Climatic Research Laboratory's records of the length of time during which a man may remain comfortable in a sleeping bag.

c. The same amount of basic heat loss may be withstood over any period of time. This is probably the case, but the data to substantiate it is not available. It is possible that for low activity the sharp gradient of extreme cold may make a loss of 80 Calories unendurable. For this reason the curves have not been plotted for the first hour.

d. Tolerance times can also be computed from the basic clo chart (Figure 9, following page 14) by taking the length of exposure and dividing it into the total number of Kg.Cals/M^2 of stored body heat to be lost before reaching the limit of cold tolerance. (80 Kg.Cals/M^2 is assumed to be a safe amount to be lost for men who are awake and 40 Kg.Cals/M^2 is assumed to be the total number which a sleeping man can lose without being awakened by the cold.)

For example, to compute the length of time for which a 4 clo suit could provide adequate protection at -5°F. for a man sitting still -

(1) Subtract the number of Kg.Cals/M^2 which he is producing (i.e. 50) from the number which he should produce in order to keep in equilibrium at -5°F. (i.e. 90). This gives the difference of 40 Kg.Cals/M^2/hr.

(2) Since a total loss of 80 Kg.Cals/M^2 is assumed to be the limit of safety, it follows that the tolerance time will be 80 ÷ 40, or two hours.

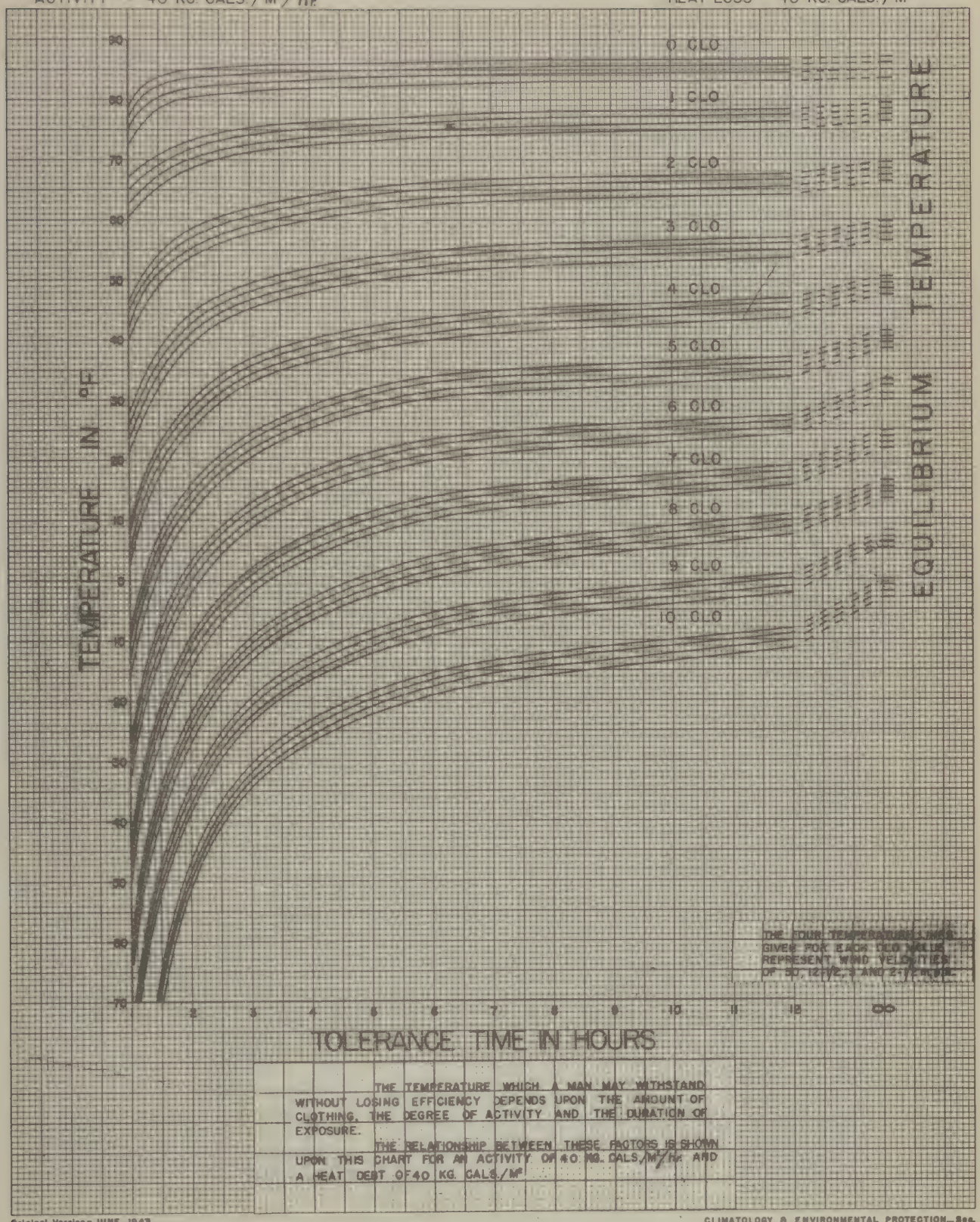
e. If the tolerance time and temperature are known, the clo value of the clothing assembly can be computed in a similar manner.

f. If the tolerance time and clo value are known, the temperature can be computed at which the man is in thermal equilibrium, or the limits of tolerance at other temperatures may be determined.

SLEEPING

ACTIVITY – 40 KG. CALS./M²/hr.

HEAT LOSS – 40 KG. CALS./M²



THE TEMPERATURE WHICH A MAN MAY WITHSTAND WITHOUT LOSING EFFICIENCY DEPENDS UPON THE AMOUNT OF CLOTHING, THE DEGREE OF ACTIVITY AND THE DURATION OF EXPOSURE.

THE RELATIONSHIP BETWEEN THESE FACTORS IS SHOWN UPON THIS CHART FOR AN ACTIVITY OF 40 KG. CALS./M²/hr. AND A HEAT DEBT OF 40 KG. CALS./M².

Original Version – JUNE 1943
This EDITION – FEB. 1944

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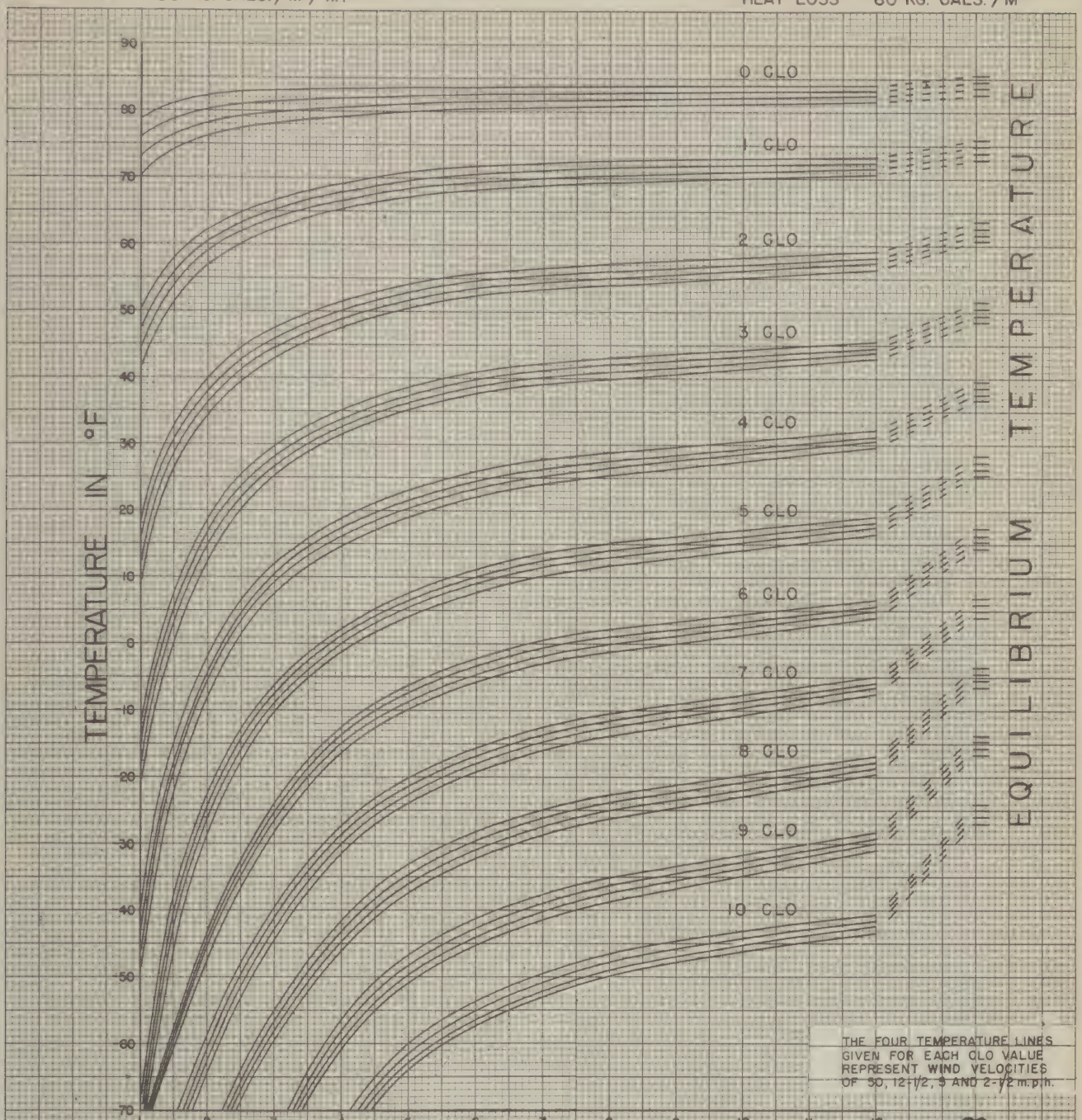
SITTING STILL

ACTIVITY — 50 KG. CALS./M²/hr.

HEAT LOSS — 80 KG. CALS./M²



THE FOUR TEMPERATURE LINES GIVEN FOR EACH CLO VALUE REPRESENT WIND VELOCITIES OF 50, 12-1/2, 5 AND 2-1/2 m.p.h.

THE TEMPERATURE WHICH A MAN MAY WITHSTAND, WITHOUT LOSING EFFICIENCY DEPENDS UPON THE AMOUNT OF CLOTHING, THE DEGREE OF ACTIVITY AND THE DURATION OF EXPOSURE.

THE RELATIONSHIP BETWEEN THESE CTORS IS SHOWN UPON THIS CHART FOR AN ACTIVITY OF 50 KG. CALS./M²/hr. AND A HEAT DEBT OF 80 KG CALS./M²

Original Version = JUNE 1943
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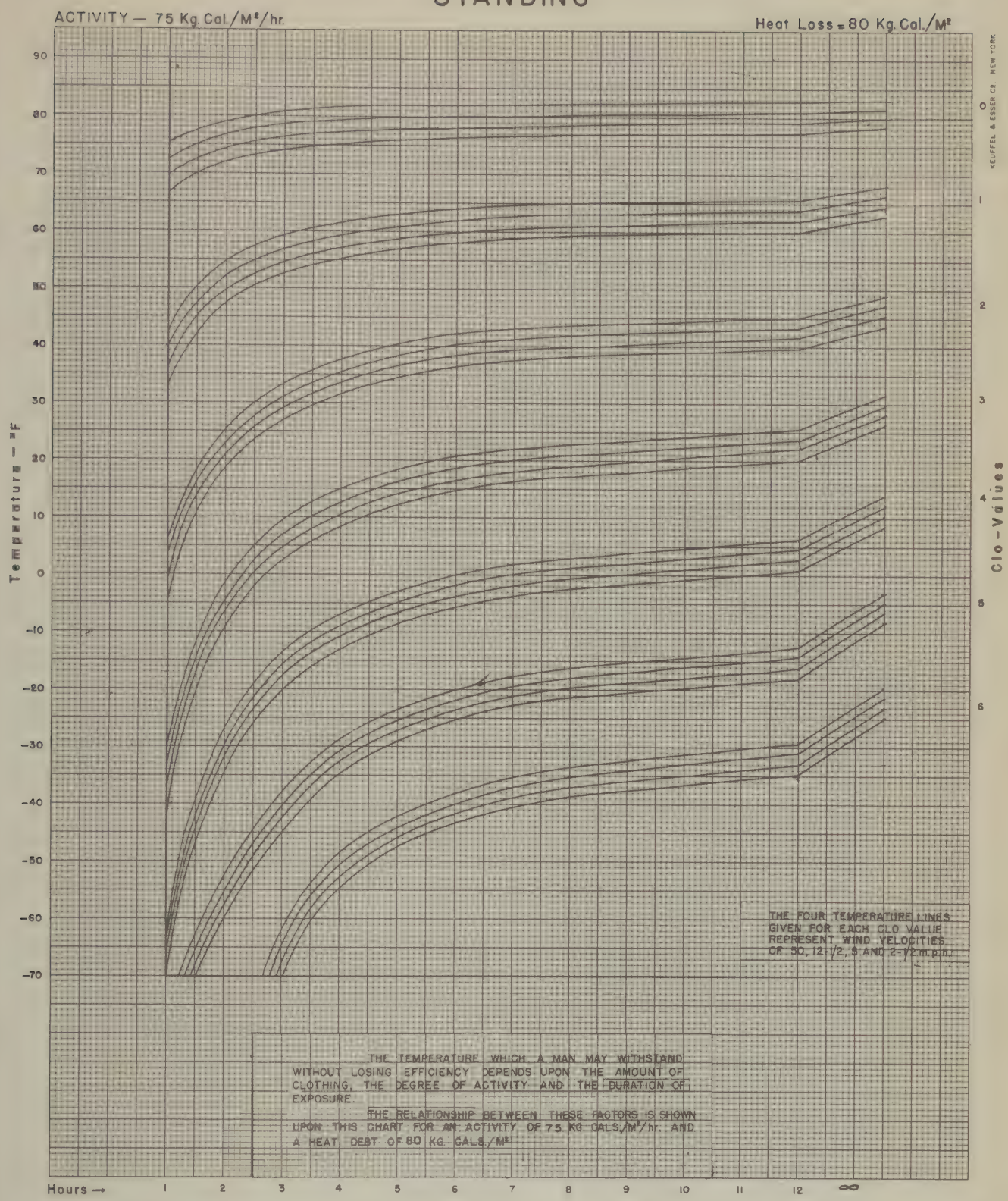
STANDARD CROSS SECTION
ENGRAVING 220 SKS TO THE HALF INCH

STANDING



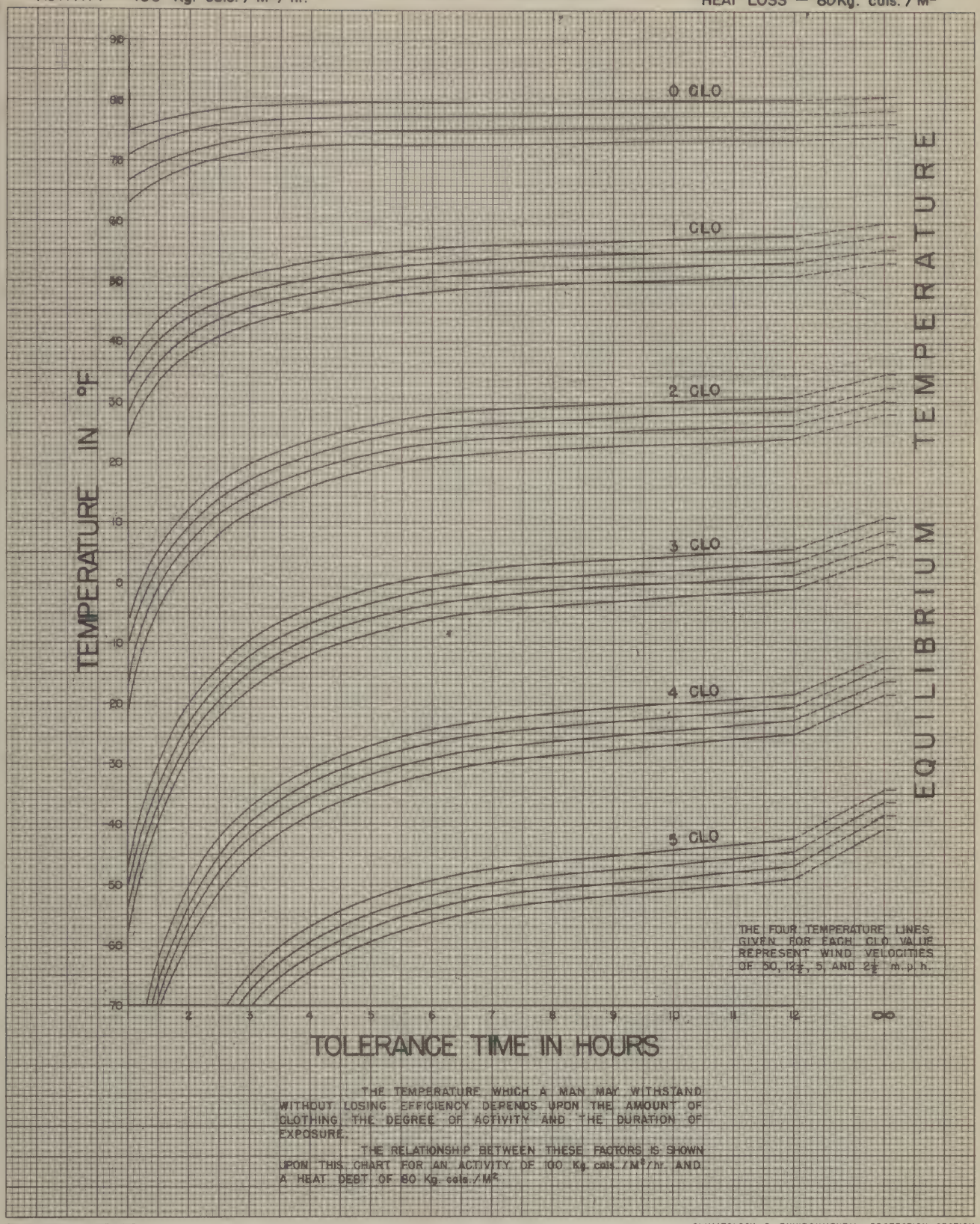
Original Version = JUNE 1943
This EDITION = FEB 1944

CLIMATOLOGY & ENVIRONMENTAL PROTECTION Section
Research & Development Branch — O.Q.M.G.

SLOW WALKING

ACTIVITY — 100 Kg. cals. / M²/ hr.

HEAT LOSS — 80Kg. cals. / M²



THE TEMPERATURE WHICH A MAN MAY WITHSTAND WITHOUT LOSING EFFICIENCY DEPENDS UPON THE AMOUNT OF CLOTHING, THE DEGREE OF ACTIVITY AND THE DURATION OF EXPOSURE.

THE RELATIONSHIP BETWEEN THESE FACTORS IS SHOWN UPON THIS CHART FOR AN ACTIVITY OF 100 Kg. cals. / M²/hr. AND A HEAT DEBT OF 80 Kg. cals. / M².

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RESEARCH & DEVELOPMENT BRANCH O. Q. M. G.

APPENDIX III

The proportionment of heat loss from various parts of the body is normally taken from the DuBois figures as follows:

Forehead	3.5%
Occiput	3.5%
Trunk	36.0%
(precordium 9%)	
(scapula 9%)	
(abdomen 9%)	
(kidney 9%)	
Upper thigh	9.0%
Lower thigh	9.0%
Leg (calf)	13.0%
Foot	7.0%
Upper arm	7.0%
Forearm	7.0%
Hand	5.0%
TOTAL	100.0%